

Article

Probabilistic Modelling of Parcel Area Uncertainty: Implications for Land Administration and Urban Planning

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Abstract

Parcel area sits at the intersection of urban planning, land administration and land surveying. It underpins development intensity, floor area allocation, minimum lot thresholds, land readjustment and value capture mechanisms. Yet discrepancies between modern measurements and ownership titles are usually evaluated through fixed tolerance formulas rather than quantified confidence intervals. While coordinate precision is routinely specified, the uncertainty of the derived parcel area is seldom expressed explicitly, limiting the traceability of planning calculations based on cadastral geometry. This paper presents a variance-based formulation for estimating parcel area uncertainty from boundary coordinates. Using the Gauss area function and first-order propagation, vertex precision is translated into parcel-level confidence intervals based on horizontal RMS parameters commonly reported in cadastral practice, including documented transformation accuracy. The Greek cadastre provides an illustrative case combining a national GNSS infrastructure, a unified reference system and formula-based area screening embedded in statutory workflows. Illustrative examples show how area uncertainty varies with parcel geometry and measurement origin. Absolute uncertainty increases with parcel size and boundary elongation, while relative uncertainty decreases with parcel size. A Monte Carlo analysis of the error-correlation structure shows that the diagonal, independent model is not a universal bound: depending on the structure of the transformation error and on parcel geometry it may either overstate or understate the true area uncertainty, by factors between about 0.4 and 3.5 in the cases examined. The results clarify how coordinate precision propagates into regulatory-relevant area values and support more transparent interpretation of area discrepancies in planning and land administration contexts.



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1. Introduction

Parcel area is a core cadastral attribute with direct monetary and legal consequences. It underpins valuation, taxation, compensation, and management decisions concerning real estate [1]. Differences in registered area may therefore translate into fiscal outcomes

and, in some jurisdictions, questions of liability and legal responsibility [2]. As cadastral practice has shifted from graphical and planimetric representations to coordinate-based frameworks, parcel area has become a derived quantity computed from vertex coordinates within national geodetic reference systems. In principle, the reliability of that quantity can be quantified through error propagation. In practice, the treatment of parcel area differences is often governed by deterministic tolerance rules or formula-based screening thresholds.

Across Europe and beyond, modernization has introduced positional accuracy classes, GNSS-supported surveys, and structured data models [3–5]. Stochastic modelling of coordinate and area observations is well established in geodetic adjustment theory, and methods for treating area and coordinate errors jointly have been proposed in the literature [6]. Yet the systematic propagation of coordinate uncertainty, particularly uncertainty introduced by datum transformations and mixed survey epochs, into parcel-specific area confidence intervals is rarely embedded in routine reporting. In many systems, transformation parameters and their root mean square (RMS) residuals are documented for technical purposes, but their implications for parcel area reliability remain implicit.

This gap becomes more visible in cadastres undergoing modernization and large-scale digital conversion. The transformation of non-digital or historically surveyed cadastral maps into unified national reference systems has been widely studied, particularly with respect to adjustment, deformation, and residual error [7,8]. Many national programs must manage the coexistence of legacy coordinates of heterogeneous quality with data acquired through modern geodetic infrastructures [9]. While these transformation processes acknowledge positional uncertainty, the resulting stochastic effects are seldom propagated through geometric functions such as area. Consequently, parcels with substantially different positional reliability may satisfy the same deterministic area tolerances, leaving their relative geometric confidence indistinguishable in routine evaluation.

Within the European Union, cadastral parcels constitute a core spatial data theme under the INSPIRE Directive, and international domain models such as the Core Cadastral Domain Model and its successors emphasize standardized representation of geometry and quality [10]. Although ISO-based frameworks provide vocabulary and structure for reporting positional accuracy, parcel-level area confidence intervals are not commonly implemented as explicit quality elements in practice. This disconnect limits the interpretability of geometric reliability in interoperable spatial data infrastructures and in planning processes that depend on cadastral geometry.

Greece provides an illustrative case of these broader conditions. The Hellenic Cadastre operates in HGRS87, supported by a national GNSS infrastructure (HEPOS) and the HTRS07 realization of ETRS89 [11]. Official transformation models between these systems report nationwide RMS values, and cadastral specifications define zone-based positional bands and formula-driven area tolerances. At the same time, historical Bessel-based datums and legacy plans remain embedded in the cadastral fabric, requiring transformation into the operational frame. Although compatibility is assessed through deterministic criteria, parcel-specific propagation of coordinate uncertainty into area reliability is not formally computed or recorded.

This study introduces a unified formulation for estimating parcel area uncertainty under such mixed-datum conditions. Building on the Gauss area function and standard error propagation theory, the approach links vertex coordinate precision, including transformation RMS values, to a parcel-level area variance expression. The formulation accommodates direct RTK acquisition in the operational frame as well as transformation from legacy coordinate systems and is designed to operate under limited covariance reporting where only

RMS values are available. The method complements existing tolerance rules by converting coordinate RMS into parcel-level area confidence intervals.

2. Background

2.1. Accuracy Standards in Modern Cadastres

In contemporary land administration systems, parcel geometry underpins taxation, valuation, compensation, subdivision control, and land readjustment. These functions depend not only on the legal definition of boundaries but on the reliability of the coordinates that represent them and, on the area, derived from those coordinates. When parcel area determines fiscal obligations or development rights, differences measured in square meters are not merely technical discrepancies; they carry regulatory and financial consequences.

Over the past three decades, many cadastres have shifted from map-scale representations and graphical tolerances toward coordinate-based systems maintained in national geodetic reference frames. GNSS infrastructures and digital data models have made it possible to specify positional accuracy numerically rather than indirectly through map scale [3]. At the same time, cadastral law has not been recast as pure geodesy. Boundary definition remains a legal act supported by measurement, not determined by it [5,12]. In practice, jurisdictions distinguish between the legal boundary, its geometric representation, and the parcel area derived from that geometry [5].

Two broad approaches structure accuracy control. The first is deterministic. It defines fixed admissible deviations, for example maximum planimetric error by land-use zone or formula-based area thresholds linked to parcel size and perimeter. Such rules favor administrative efficiency and predictable decision-making in high-volume cadastral operations. The second approach is stochastic. It treats boundary vertices as random variables with associated variance–covariance structure and propagates coordinate uncertainty through geometric functions such as length and area. Reliability is then expressed through standard deviations and confidence intervals. The mathematical basis is standard in geodetic adjustment theory, yet its incorporation into cadastral reporting remains uneven.

In practice, European systems combine these logics. Deterministic thresholds are retained for routine acceptance, update procedures, and dispute screening. Variance-based reasoning appears in network adjustments, technical quality reports, and in expert analysis when precision becomes contested [4,5]. The balance reflects institutional history as much as technical capability.

Comparative experience illustrates the range of configurations. Switzerland operates a coordinate cadastre in which boundary points meet centimeter-level tolerances and coordinates are legally authoritative [13]. Germany and Austria have progressively upgraded legacy graphical products toward coordinate reliability through homogenization and systematic re-survey, while managing heterogeneous historical layers [3,14]. The Netherlands applies explicit area comparison formulas, linking acceptable discrepancies to parcel size and distinguishing between urban and rural contexts [15]. Romania and Turkey codify tolerance rules tied to point precision and perimeter, translating geodetic reasoning into operational criteria [16,17]. The United Kingdom follows a different model: under the general boundaries’ doctrine, title plans are indicative and legal boundary determination relies primarily on evidentiary interpretation rather than fixed numeric tolerances [12].

There is no single European accuracy model. Yet the shift toward automated validation and interoperable geospatial systems requires geometric reliability to be explicitly quantified. As cadastral data are increasingly integrated into planning systems and digital spatial infrastructures, expectations regarding documented positional and areal accuracy have intensified. Whether through fixed thresholds or stochastic measures, modern cadastres are

required to articulate how precise their parcel geometry is, and what that precision implies for land governance decisions.

2.2. Comparative Review of European Practices and Evolution

The European cadastre matured in diverse legal cultures yet faces common technical pressures. Historic survey eras left behind heterogeneous map quality. Photogrammetric mosaics, paper plans, and partial coordinate adjustments introduced position-dependent distortions. Modern operations rely on GNSS and coherent reference frames, so legacy data must be reconciled to achieve seamless coverage. Quality assessment is therefore both a technical and institutional task. It defines the acceptable gap between past and present geometry, decides when to rectify, and sets thresholds that balance legal stability with spatial truth [3,4].

Switzerland's model is the cleanest expression of a coordinate cadastre. The official survey sets numerical tolerances by zone. In built-up areas boundary points are surveyed to centimetre-level, legally binding coordinates, with numerical tolerances defined by zone; parcel boundaries are the most tightly controlled layer. The quality regime is therefore front-loaded. Errors larger than tolerance are corrected before survey plan submission. Area is a derivation of high-precision coordinates, so separate area tolerances are rarely needed [13].

Germany's path shows how a federated system converges on quality. Older Liegenschaftskarte sheets, often at 1:1000 or 1:2500, were digitized with typical positional accuracy ranging from decimeters to about a meter depending on scale and source. The ALKIS reform and the expansion of the Koordinatenkataster shifted emphasis to rigorous survey and adjustment. New boundary points achieve few-centimeter standard deviations, and survey regulations, set by the individual Länder, apply closure and accuracy criteria to new work. State offices still manage legacy distortions where original map provenance limits achievable precision. Quality assessment works on two levels. It improves legacy geometry through adjustment and targeted field verification. It enforces strict standards on new surveys so that, over time, the coordinate fabric dominates the map's quality [3,18].

The numerical requirements are codified by the individual Länder rather than federally. In Baden-Württemberg, for example, the administrative regulation for cadastral surveys expresses the admissible area difference as $ZF = 0.2 \cdot \sqrt{F}$, with F the parcel area in square metres [19]. This is structurally the same square-root form as the Dutch fallback rule, corresponding to an effective coefficient of about 2 when the area is expressed in are. The same square-root functional form therefore appears in more than one jurisdiction, with admissible area differences growing sublinearly with parcel size.

Austria runs a dual system. The Grenzkataster, established under the Surveying Act as the binding record of parcel boundaries [20], secures legally binding, centimeter-level coordinates where parcels enter that regime with neighbor consent and precise re-survey. The broader "Digital Cadastral Map" carries variable accuracy that reflects survey epochs. Studies show urban parcels often cluster around 0.4 m standard deviation in position, while some rural districts exhibit around one meter or more. Authorities communicate this disparity and encourage conversion projects. Quality assessment combines statistical comparison of new surveys to existing coordinates, legal prudence to avoid needless record churn, and systematic upgrades where the benefit of certainty outweighs the disruption [14,21].

The Netherlands makes its tolerance policy explicit for area. The continuous digital cadastral map derives from historic cartography and subsequent adjustments. Boundary point standard deviations near 0.20 m in built areas and about 0.40 m in rural settings are typical for map-derived coordinates that lack recent field remeasurement. The Kadaster

triggers redressing of a registered area when the absolute difference between the computed and the registered area exceeds twice the standard deviation of the computed area; where that standard deviation is not, or cannot be, computed, a fallback tolerance $q\sqrt{a}$ applies, in which a is the parcel area expressed in are (1 are = 100 m²) and q takes the values 1 for terrestrially surveyed areas, 5 for built-up areas and 10 for rural areas [22]. With the area in square metres these correspond to about $0.1\sqrt{A}$, $0.5\sqrt{A}$ and $\sqrt{A}$ respectively. In this formulation the standard deviation of the computed area is used where it is available, and the square-root expression serves as the fallback where it is not [4,15].

Romania specifies precision by reference to plan scale rather than through a single national point-accuracy figure. The technical specifications for systematic cadastral works require the precision corresponding to the graphic precision of the plan scale, taking a graphic error of 0.2 mm, with 1:5000 applied outside and 1:2000 inside the built-up area [23]; separate provisions on cadastral documentation distinguish the identification of fenced from unfenced boundaries. No perimeter-based area tolerance is codified nationally. It is nonetheless instructive that combining a point precision p with a parcel perimeter P yields an area tolerance of the order $T = P \cdot p$; for a square hectare with P of about 400 m and p of 0.10 m this gives roughly 40 m². Such an expression scales with shape, so that thin parcels with a larger perimeter at the same area would earn higher tolerances, but it is an illustrative derivation rather than a codified national formula [16].

In France the vectorized cadastre (PCI Vecteur) carries scale-dependent positional tolerances rather than a single stated standard deviation, coarser for small-scale legacy mapping and finer for large-scale urban sheets. Where re-surveys are performed using GNSS or total stations, new coordinates are tied to the Réseau Géodésique Français (RGF93), the French realization of ETRS89, and reach centimetre-level precision on new boundary points. These high-accuracy coordinates coexist with legacy vector data, whose quality class is recorded through metadata rather than rectified by default [20,21]. France thus distinguishes between map accuracy, for fiscal mapping, and geodetic precision, for new survey operations. Several departmental cadastral modernization projects (e.g., Remaniement Cadastral) apply tighter positional tolerances for built-up parcels to support integration with topographic databases [22].

Italian cadastral technical standards (Circolare 2/1988 and successive circulars) set planimetric tolerances of the order of a decimetre for new boundary points, somewhat tighter in urban than in rural parcels. Area acceptance is governed by these circulars, which define surface-difference tolerances in relation to parcel area rather than by a fixed perimeter-proportional rule; reported acceptance bands are on the order of a few percent of the registered area. The tolerance recognizes the legacy mix of sources and serves as an acceptance threshold rather than a stochastic uncertainty estimate. Some regional modernization projects (e.g., in Emilia-Romagna and Lombardia) report positional accuracies below ± 0.05 m for RTK-derived parcels, documented using ISO 19157 data quality metadata and INSPIRE-compliant cadastral parcel schemas [23].

Spanish cadastral regulations (Real Decreto 417/2006, Orden HAP/566/2013) define positional tolerances according to data source. For graphic (digitized) parcels, acceptable positional error is coarser and depends on the source and zone. For parcels surveyed with GNSS or total stations, the standard deviation of boundary coordinates must not exceed ± 0.05 m. For the exchange of information between the Cadastre and the Property Registers, the joint resolution of 26 October 2015 sets the geometric precision at ± 0.20 m or ± 0.40 m according to whether the graphical representation is digitised over urban or rural cadastral cartography, while a representation derived from a topographic survey must achieve a maximum error below 25 cm with 85% of points within 20 cm [24].

Area tolerance in Spain is treated functionally: differences of the order of a few percent between registered and measured areas are accepted without correction [24]. Parcels are further distinguished by data source and coordinate quality, from GNSS-surveyed coordinates through adjusted or photogrammetric coordinates to legacy vectorized geometry, with correspondingly looser positional expectations.

Turkey sets error limits by source and scale. The national regulation on large-scale map production specifies a horizontal accuracy of a few centimetres for detail points and a limit of 8 cm between two independent determinations of principal parcel points [25]. Legacy graphical maps and early photogrammetric products carry ground errors ranging from decimetres to several metres, while modern digital mapping and surveys tied to the national frame reach centimetre level. In renewal projects, field coordinates are compared to existing records: differences within the source-specific limit are accepted as noise inherent to the source, and larger differences trigger correction. The quality regime is explicit about legacy uncertainty bands, and it narrows them through re-survey and harmonization [17].

The United Kingdom, by design, does not fix legal boundaries by coordinate. The Land Registry’s title plan carries general boundaries, normally aligned to Ordnance Survey base mapping. OS publishes map accuracy, but the legal boundary is proven by evidence rather than by a numeric tolerance in the registry plan. This approach avoids a false sense of precision in settings where fences, walls, and conveyances tell the stronger legal story. It also underscores a key point for comparative work. Cadastral accuracy is not solely technical. It is anchored in legal doctrines that may prioritize different evidence under dispute [5,12].

These national examples demonstrate an evolution from implicit tolerances and map-scale heuristics to explicit tolerance classifications and formulas. The common denominator is transparency. Each system communicates what accuracy means at the point and parcel level, and how differences are handled. Where coordinates are law, tolerances are small and upfront. Where historical fabric dominates, tolerances are used to triage which differences matter and which do not. Where legal doctrine resists numeric fixation, quality control shifts to the provenance and clarity of the underlying map [3,12].

It’s also worth noting that within the EU, quality documentation and metadata are increasingly aligned with ISO 19157 and the INSPIRE approach to harmonized reporting, ISO 19157 provides the reference vocabulary and reporting model for geospatial data quality. It specifies which quality elements to assess, how to define measures, and how to document evaluation results so they are comparable and reusable across systems [25]. The standard prescribes how cadastral agencies report positional accuracy, logical consistency, and completeness while leaving each jurisdiction to choose thresholds that fit its legal and operational needs. For high-volume production, agencies combine full inspection of critical deliverables with acceptance sampling to control effort at scale, drawing on ISO 2859-2 plans [26]. For example, Greece has framed cadastral QA plans using that model [27]. Table 1 summarizes the aforementioned descriptions.

Table 1. Summary of positional standards and area tolerance practices.

Country	Typical Positional Standard for Parcel Vertices	Area Tolerance or Comparison Rule
Switzerland	Centimetre-level, legally binding boundary coordinates; numerical tolerances defined by zone. Area derives from high-precision coordinates.	Not separately specified for parcels.
Germany	New coordinate-based surveys at few-centimeter standard deviations. Legacy digitized maps often in the 0.3–1.0 m range. Closure and accuracy criteria set in the Länder survey regulations.	No single national area formula. Acceptance relies on point tolerances and closure. Large mismatches prompt investigation or re-survey.

Table 1. *Cont.*

Country	Typical Positional Standard for Parcel Vertices	Area Tolerance or Comparison Rule
Austria	Grenzkataster parcels at centimeter level and legally binding. Graphical cadastre varies. Urban districts near 0.4 m standard deviation. Some rural districts around one meter or more.	No universal formula. Differences judged by source quality and local practice.
Netherlands	Map-derived coordinates about 0.20 m in built areas and 0.40 m in rural areas. New terrestrial surveys at 5–10 cm.	Redressing if $ \Delta > 2\sigma$ of the computed area; fallback $q\sqrt{a}$ with a in are and $q = 1$ (terrestrial)/5 (built-up)/10 (rural), i.e., about $0.1\sqrt{A}$, $0.5\sqrt{A}$ and $\sqrt{A}$ with A in m^2 .
Romania	Precision referenced to the graphic precision of the plan scale (1:2000 built-up, 1:5000 outside built-up; 0.2 mm graphic error).	No codified national area formula. Illustrative screen $T = P \cdot p$ scales with perimeter; not a statutory rule.
Turkey	Error limits by source and scale: decimetre-to-metre errors for legacy graphical and photogrammetric sources; centimetre level for modern digital surveys.	Differences within source-specific error limits accepted. Larger differences corrected during renewal.
United Kingdom	Title plan shows general boundaries on OS mapping. OS large-scale maps have meter-level absolute accuracy bands. Coordinates are not normally legally definitive for boundaries.	No numeric tolerance in title plans. Boundary precision determined by legal evidence.
France	Vectorized cadastral parcels (PCI Vecteur) carry scale-dependent tolerances, coarser for legacy small-scale mapping and finer for urban sheets; new GNSS surveys tied to RGF93 reach centimetre level.	Legacy mapping not corrected; modernization projects apply tighter positional tolerances for built-up areas.
Italy	Historic graphical maps of order a metre; new surveys tied to RDN2008/ETRF2000 of order a decimetre for boundary points.	Surface-difference tolerance defined in Circolare 2/1988 and successive circulars, in relation to parcel area (order of a few percent).
Spain	Coarser positional expectations for digitized legacy parcels; new GNSS surveys $\leq \pm 0.05$ m; cadastral–registry coordination within about ± 0.20 m (urban)/ ± 0.40 m (rural).	Accepted area difference in the order of a few percent between registered and measured values; parcels further distinguished by data source and coordinate quality.
Greece	Operationally in HGRS87. Field control via HEPOS and ETRS89 realization. Deterministic positional bands by zone exist in specifications. Transformation RMS between ETRS89 and HGRS87 ≈ 8.3 cm nationally.	De facto area screening uses perimeter- and shape-aware formula with equivalent-square construct and urban/rural offsets.

2.3. Limitations of Parcel Area Accuracy Modelling in the Hellenic Cadastre

The Hellenic Cadastre is a national parcel-based system established in the 1990s, designed to replace descriptive land books with georeferenced property units. The legal basis rests on the law of establishment and the law of operation and corrections. Ktimatologio S.A., now part of the Hellenic Cadastre legal entity, supervises contracting, quality control of deliverables, and maintenance of the database.

The Hellenic Cadastre operates within the Greek Geodetic Reference System 1987 (HGRS87), the projected coordinate framework used for official cadastral registration [28]. Modern field surveys are tied to the national GNSS infrastructure (HEPOS), which realizes ETRS89 in Greece through the Hellenic Terrestrial Reference System 2007 (HTRS07). An official transformation is applied between HTRS07 and HGRS87 for operational purposes, with a nationally reported root mean square (RMS) value on the order of 8.3 cm in planimetry [11]. This transformation accuracy represents a documented stochastic characteristic of the national reference framework and directly affects coordinates derived from GNSS observations. The main reference frame pathways and their dominant uncertainty components are summarized in Table 2.

Table 2. Reference frames and dominant uncertainty sources in Greek cadastral practice.

Process	Reference Frame Path	Dominant Precision Term	Typical Use
Direct RTK survey	HTRS07 realization of ETRS89, transformed to HGRS87 for operations	Centimeter-level RTK precision plus HTRS07 to HGRS87 transformation RMS on the order of 8.3 cm if applied	New boundary surveys, updates, control densification
Transformation from old Greek datum (OVGRD)	Bessel-based legacy to HGRS87	Spatially variable transformation residuals, often larger than RTK noise	Migration of legacy plans, urban plan alignment
Transformation from post-war remeasured datum (NVGRD)	Revised Bessel to HGRS87	Similarly to above, with regional variation tied to remeasurement epoch	Legacy control and plan adjustments
Orthophoto support	Imaging blocks referenced to HGRS87	Map-scale dependent planimetric accuracy in meters for older imagery, tighter for modern block	Visual interpretation, QA support

At the same time, the cadastral fabric incorporates legacy material originating from earlier Greek datums based on the Bessel ellipsoid, including pre-war and post-war survey products. These datasets were produced under heterogeneous control conditions and subsequently transformed into HGRS87.

In Greece, the coexistence of multiple historical realizations preceding HGRS87 further complicates the geodetic framework. The Old Greek Datum (GRD), based on the Bessel (1841) ellipsoid, was implemented through two separate adjustments, the “old Bessel” (1940s) and the “new Bessel” (1980s), without a unified national re-adjustment. Both were used with the Hatt and 3° Transverse Mercator (TM3°) projections. As documented in analyses of RTK use in the old datum [29], the underlying measurements date mainly from 1940–1970 and exhibit inconsistencies, local distortions, and loss of triangulation control. Polynomial transformations to HGRS87 typically achieve mean accuracies of 10–15 cm at national scale, with additional orientation discrepancies [30]. Following Ampatzidis et al. [31], the two realizations are referred to here as the Old Version of Greek Datum (OVGRD) and the New Version of Greek Datum (NVGRD).

For short baselines, parallelism between systems may be assumed with limited impact. At larger extents, scale differences and orientation offsets introduce systematic effects. As in many transitional cadastral systems, the integration of such material introduces spatially variable transformation residuals. While transformation models and their overall RMS statistics are documented, residual patterns are not uniform across the territory and may depend on network density, epoch, and local adjustment history [32]. Coordinate values inherited from older datums therefore embed transformation residuals and local deformation effects, which directly affect parcel area.

Accuracy governance in the Greek cadastre combines reference frame standardization with deterministic acceptance criteria. Technical specifications define positional tolerance bands that differ between urban and rural zones. In parcel update workflows, new survey coordinates are compared with registered geometry, and compatibility is assessed against these bands. If deviations remain within the specified limits, the geometry is accepted as consistent with the record.

Area comparison is handled through a formula-based screening rule that accounts for parcel size and shape as described in Article 13a of Law 2664/1998 (Equation (1)):

$$A_{tol} = [(\sqrt{E} + 2U_0)^2 - E] \times \frac{P}{P_t}. \quad (1)$$

E is the registered parcel area (m²); P is the registered parcel perimeter (m); $P_t = 4\sqrt{E}$ is the perimeter of the square having area E ; P/P_t is a dimensionless factor that adjusts the admissible discrepancy according to parcel shape; and U_0 is an administratively defined

offset (m), specified separately for urban and rural zones in the technical guidelines of the Hellenic Cadastre. The resulting quantity A_{tol} (m²) represents a deterministic area tolerance used for administrative screening; it does not correspond to a defined statistical confidence level and is not derived from variance propagation.

This expression scales the allowable area difference according to both parcel area and geometric configuration. The offset parameter differs by zone, reflecting a policy choice to tolerate larger deviations in rural contexts. In practice, this rule functions as an indicative administrative filter: if the difference between registered and newly computed area falls within A_{tol} , the discrepancy is treated as acceptable measurement variation.

The regulatory status of this rule is, however, limited. Its mathematical form and an accompanying cap of seven per cent on the acceptable deviation were set for areas under cadastral survey by decision 461/03/2008 of the Hellenic Cadastre board (Government Gazette B' 1510/31.7.2008); a subsequent amendment raising the cap to ten per cent for areas surveyed under Law 2308/1995 was not published. For areas already under an operating cadastre the rule was withdrawn by decision 475/06/2009 (Government Gazette B' 500/18.3.2009), where the computed deviation is explicitly indicative and non-binding, and Article 13a is generally regarded as never having been activated for operational transactions. Under Law 4602/2019 the requirement associated with a spatial change is a geometric-change diagram accompanied by an engineer's declaration of admissibility, rather than an area-tolerance test.

The requirement actually enforced on cadastral diagrams is instead a coordinate-accuracy specification. Horizontal accuracies of the order of 0.40 m in urban and 1.00 m in rural areas are required per coordinate component (a two-dimensional RMS of about 0.56 m and 1.41 m, respectively), together with an absolute positional accuracy of about 0.98 m and 2.45 m at the 95% confidence level. The operational framework is therefore already expressed through coordinate root-mean-square values and confidence levels rather than through a binding deterministic area formula. Propagating documented coordinate uncertainty into a parcel-area confidence interval is consistent with that framework, and is the approach developed here.

The framework exhibits internal consistency in that surveys, transformations, validation rules, and database topology are governed by a single, standardized reference and rule set. As implemented, the system is coherent and reproducible. However, for parcel-level uncertainty analysis, three structural characteristics require attention.

First, coordinate precision and transformation RMS values are not propagated into parcel-specific area uncertainty. For GNSS-based surveys, centimeter-level precision and the national transformation RMS are known quantities. For legacy transformations, overall RMS statistics are available from adjustment studies. Yet these stochastic parameters are not systematically carried through the Gauss area function to produce a variance or confidence interval for the parcel area. Area reliability is inferred indirectly through deterministic screening rather than computed explicitly.

Second, parcels derived through different measurement pathways are evaluated under the same area tolerance formula. A parcel surveyed directly using RTK methods and a parcel assembled through transformation of a legacy Bessel-based plan may both satisfy the deterministic acceptance rule, even though their underlying coordinate uncertainty structures differ. The current model does not distinguish between measurement-driven and transformation-driven uncertainty at the level of reported area reliability.

Third, the coexistence of multiple survey epochs introduces heterogeneity that remains statistically unexpressed. In urban areas, parcels are increasingly updated through direct GNSS surveys tied to HEPOS. In other areas, legacy geometry remains transformation-dominant. Although positional tolerance bands and area screening rules provide opera-

tional thresholds, they do not produce parcel-level indicators of geometric reliability that reflect this heterogeneity.

These characteristics do not imply technical deficiency. They reflect a governance choice: prioritize clear acceptance criteria and administrative efficiency over parcel-specific stochastic reporting. Similar configurations are observed in other European systems that combine coordinate modernization with deterministic area comparison rules. The Greek case is therefore not exceptional; it is representative of a mature coordinate-based cadastre in which transformation accuracy is quantified, yet not explicitly propagated into derived geometric attributes.

For the purposes of this study, the Greek cadastral framework offers a clearly defined analytical setting. The reference systems are known, transformation RMS values are documented, and the deterministic area tolerance formula is explicit. At the same time, parcel-specific area confidence intervals are not part of the official accuracy model. This combination allows examination of how documented coordinate uncertainty can be formally linked to parcel area variance under realistic operational conditions, without altering the existing deterministic acceptance structure (see Table 2).

3. Methodology

Let a parcel be defined by n boundary vertices with projected planar coordinates (x_i, y_i) , expressed in a common reference system. The parcel area E is computed using the Gauss formula (Equation (2)):

$$E = \frac{1}{2} \sum_{i=1}^n x_i (y_{i+1} - y_{i-1}) \quad (2)$$

where cyclic indexing is assumed and x_i, y_i denote Easting and Northing coordinates, respectively. The formulation assumes a closed polygon in a planar projection; projection distortions are not considered.

Since area is a function of the vertex coordinates, coordinate uncertainty propagates into area uncertainty. Using first-order error propagation, the variance of E is:

$$\sigma_E^2 = A C_x A^T \quad (3)$$

where A is the Jacobian vector of partial derivatives of E with respect to the coordinate components, and C_x is the variance–covariance matrix of the coordinates. Equation (3) results from linearization of the Gauss area function; higher-order terms are neglected, which is justified for small coordinate perturbations relative to parcel dimensions.

In operational cadastral workflows, complete covariance matrices are rarely available. RTK outputs and legacy transformations typically provide only root mean square (RMS) indicators. We therefore assume a diagonal covariance matrix. Under this assumption, Equation (3) reduces to:

$$\sigma_E^2 = \sum_{i=1}^n \left(\frac{\partial E}{\partial x_i} \right)^2 \sigma_{x_i}^2 + \left(\frac{\partial E}{\partial y_i} \right)^2 \sigma_{y_i}^2 \quad (4)$$

The derivatives derived from Equation (2) are:

$$\left(\frac{\partial E}{\partial x_i} \right)^2 = \frac{1}{4} (y_{i+1} - y_{i-1})^2, \quad \left(\frac{\partial E}{\partial y_i} \right)^2 = \frac{1}{4} (x_{i+1} - x_{i-1})^2$$

Substituting these into Equation (4) yields:

$$\sigma_E^2 = \frac{1}{4} \sum_{i=1}^n \left[(y_{i+1} - y_{i-1})^2 \sigma_{x_i}^2 + (x_{i+1} - x_{i-1})^2 \sigma_{y_i}^2 \right]$$

In nationwide transformations and RTK services, uncertainty is typically expressed as a single horizontal RMS value rather than separate Easting and Northing components. Let σ_{r_i} denote the total horizontal uncertainty of vertex i . Assuming equal component variances,

$$\sigma_{x_i}^2 = \left(\frac{1}{\sqrt{2}}\sigma_{r_i}\right)^2, \sigma_{y_i}^2 = \left(\frac{1}{\sqrt{2}}\sigma_{r_i}\right)^2 \quad (5)$$

which implies:

$$\sigma_E^2 = 0.125 \sum_{i=1}^n \left[(x_{i+1} - x_{i-1})^2 + (y_{i+1} - y_{i-1})^2 \right] \sigma_{r_i}^2 \quad (6)$$

In most practical applications only a single RMS value is available for an entire survey or transformation. Assuming a common uncertainty,

$$\sigma_{r_i} = \sigma_r \forall i,$$

Equation (6) simplifies to:

$$\sigma_E^2 = 0.125 \sigma_r^2 \sum_{i=1}^n d_i^2 \quad (7)$$

where

$d_i^2 = (x_{i+1} - x_{i-1})^2 + (y_{i+1} - y_{i-1})^2$ and d_i represents the projected distance between vertices $i + 1$ and $i - 1$. The term d_i has units of meters, and σ_E therefore has units of square meters. The geometric term $\sum d_i^2$ depends solely on parcel configuration. The term increases with the spatial spread of the boundary vertices: elongation raises it, whereas increasing the number of vertices, or introducing concavity or articulation, does not raise it systematically, as shown by the simulation study in Section 4.1.

The pairing of the coordinate differences with the corresponding component variances follows directly from the partial derivatives of Equation (2): the derivative with respect to x_i involves the difference in the neighbouring Northing coordinates and the derivative with respect to y_i the difference in the neighbouring Easting coordinates. This distinction affects the propagated variance only when the Easting and Northing precisions differ; under the isotropic assumption $\sigma_x = \sigma_y$ adopted throughout this study, Equation (7) and the reported area uncertainties are unchanged.

The quantity σ_E corresponds to one standard deviation, which under the assumption of approximately Gaussian coordinate errors represents about 68% confidence for a two-sided interval. To express uncertainty at a 99% confidence level ($\alpha = 0.01$), the standard normal multiplier $z_{\alpha/2} = 2.575$ is applied:

$$s_E = 2.575 \sigma_E \quad (8)$$

For RTK mapping using HEPOS, the officially accepted nationwide RMS for the transformation from ETRS89 to HGRS87 is 8.3 cm. Throughout this study σ_r denotes the total horizontal, that is two-dimensional, root-mean-square error of a vertex, $\sigma_r = \sqrt{(\sigma_x^2 + \sigma_y^2)}$, and not a per-component value; with equal component variances this yields $\sigma_x = \sigma_y = \sigma_r / \sqrt{2}$ as used in Equation (5). The nationwide value of 8.3 cm reported for the transformation from ETRS89 to HGRS87 [11] is a total horizontal RMS in this sense and is therefore substituted directly as σ_r . Where an accuracy figure is instead published as a per-component standard deviation, it must first be converted through $\sigma_r = \sqrt{2} \cdot \sigma_{\text{component}}$ before substitution into Equation (7); omitting this conversion would understate the propagated area uncertainty by a factor of $\sqrt{2}$. The value adopted for the RTK pathway combines the field precision of the survey with the transformation uncertainty by variance addition, $\sigma_r^2 = \sigma_{r,\text{RTK}}^2 + \sigma_{r,\text{transformation}}^2$. Taking $\sigma_{r,\text{transformation}} = 0.083$ m, the rounded working value $\sigma_r = 0.10$ m accommodates

an RTK field component of $\sigma_{\text{RTK}} = \sqrt{(0.10^2 - 0.083^2)} \approx 0.056$ m, which is consistent with the horizontal precision typically achieved in network RTK practice. The value is therefore a deliberately conservative but traceable choice rather than an arbitrary rounding. Substituting into Equation (7):

$$\sigma_{E,\text{HEPOS-RTK}} = 0.035355 \sqrt{\sum_{i=1}^n d_i^2} \quad (9)$$

and at 99% confidence:

$$s_{E,\text{HEPOS-RTK}} = 0.09104 \sqrt{\sum_{i=1}^n d_i^2} \quad (10)$$

For transformation from OVGRD to HGRS87, inserting the corresponding transformation RMS into Equation (7) yields at 99% confidence:

$$s_{E,\text{OVGRD-HGRS87}} = 2.575 \sqrt{0.125 \sigma_{\text{transformation}}^2 \sum_{i=1}^n d_i^2} \quad (11)$$

For transformation from NVGRD to HGRS87, adopting a nationwide RMS of 15 cm [30], the 99% area uncertainty becomes:

$$s_{E,\text{NVGRD-HGRS87}} = 0.1366 \sqrt{\sum_{i=1}^n d_i^2} \quad (12)$$

The proposed methodology converts documented horizontal coordinate precision into parcel-specific area uncertainty using only vertex coordinates and a single RMS parameter. Correlation between vertices and potential systematic deformation effects are not modeled; the result represents an approximate stochastic estimate under the stated assumptions. The method quantifies geometric uncertainty arising from measurement and transformation processes and does not address legal boundary interpretation or ownership disputes.

The area functional is invariant under the rigid-body components of a coordinate perturbation. For a closed polygon, a common translation of all vertices leaves the area unchanged because the summed coordinate differences telescope to zero; a rigid rotation leaves it unchanged because area is preserved under isometries; and a uniform scaling about the centroid changes the area only through the square of the scale factor. Equivalently, the area gradient is orthogonal to the translation and rotation modes. A datum-transformation error combines a common-mode part (translation and rotation), a systematic scale part, and an independent residual. Only the scale component, a systematic term proportional to the parcel area and to the scale uncertainty, and the independent residual propagate into the area; the common-mode translation and rotation do not. The common-mode translation and rotation components therefore contribute nothing to the area variance, whatever their magnitude, whereas the scale component and the independent residual do contribute. For direct field surveys the independent model is a reasonable operational approximation where the error budget is dominated by independent point-positioning noise; it is not exact, because RTK coordinates may share common reference-station, atmospheric, network, transformation and adjustment components. For transformation-derived parcels the net effect of treating the reported RMS as independent per-vertex noise is not signed in general: it over-counts the area-neutral rigid-body part but may under-represent scale and spatially structured residuals, as quantified in Section 4.1. Where a full or block variance-covariance matrix is available, the same Jacobian applies to it directly.

4. Case Studies

The proposed error-propagation method is applied to three representative cadastral situations in Greece, covering direct RTK measurement and two legacy datum transformation pathways. The cases differ in size, geometric configuration, and coordinate precision in order to examine the combined influence of positional accuracy and parcel geometry on propagated area uncertainty. All reported area uncertainties correspond to the 99% confidence level, derived using Equation (8) in Section 3.

Case 1 presents a small urban parcel in Drama measured directly in HGRS87 using RTK (Figure 1). The estimated area is 134.87 m^2 . Using an adopted horizontal RMS of 0.10 m and Equation (10), the propagated area uncertainty equals 2.61 m^2 , corresponding to 1.9% of the parcel area. The parcel consists of 9 boundary vertices.

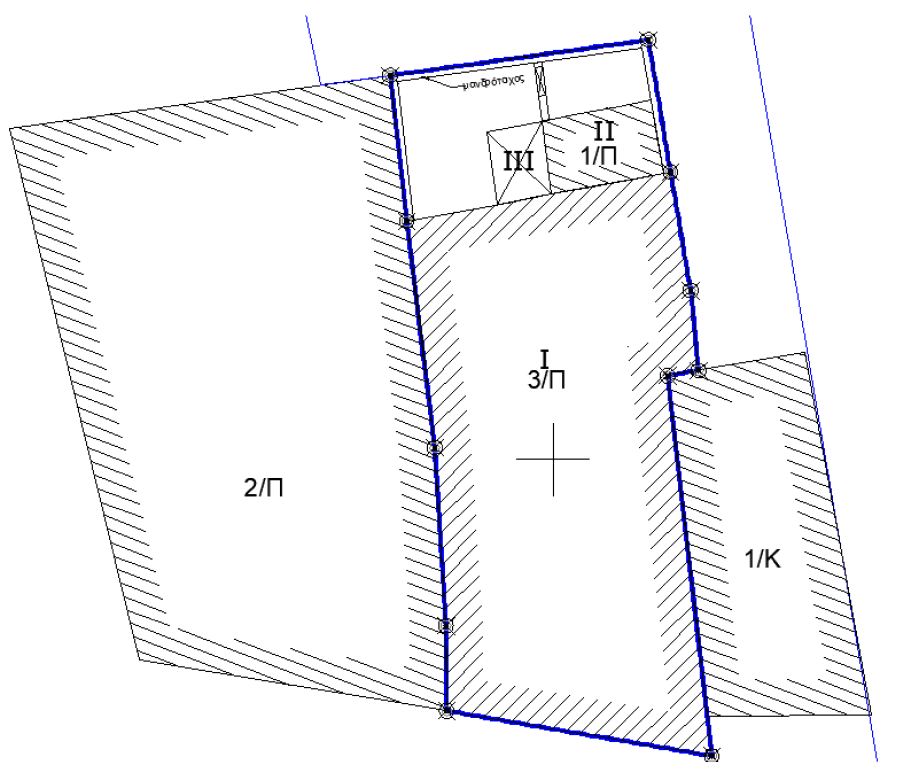


Figure 1. Urban parcel measured directly in HGRS87 (Drama, Greece). Boundary vertices were observed by network RTK and are expressed in the HGRS87 projected coordinate system (EPSG:2100). The parcel boundary is highlighted; the underlying plan is reproduced from Hellenic Cadastre records.

Case 2 presents a rural block in Choristi village whose boundaries were transformed from OVGRD to HGRS87 (Figure 2). The estimated area is 5547.67 m^2 . Using a transformation RMS of 0.17 m , adopted for this block as a conservative value slightly above the 10 to 15 cm range reported for polynomial transformations at national scale in Section 2.3, and Equation (11), the propagated area uncertainty equals 31.51 m^2 , corresponding to 0.6%. The parcel consists of 6 boundary vertices.

Case 3 presents a large rural parcel in Nea Amisos village transformed from NVGRD to HGRS87 (Figure 3). The estimated area in HGRS87 is $163,636.38 \text{ m}^2$. Using a transformation RMS of 0.15 m and Equation (12), the propagated area uncertainty equals 244.51 m^2 , corresponding to 0.2%. The parcel consists of 4 boundary vertices. Table 3 provides a summary of uncertainty estimates and Table 4 reports the area calculated directly in NVGRD prior to transformation and the area obtained after transformation to HGRS87. The absolute difference between the two areas equals 127.62 m^2 (0.078%).

This difference corresponds to about 390 ppm of linear scale and reflects the systematic scale, rotation, and local-deformation content of the datum transformation, not a random realization of coordinate uncertainty; it should not be interpreted through the stochastic confidence interval.

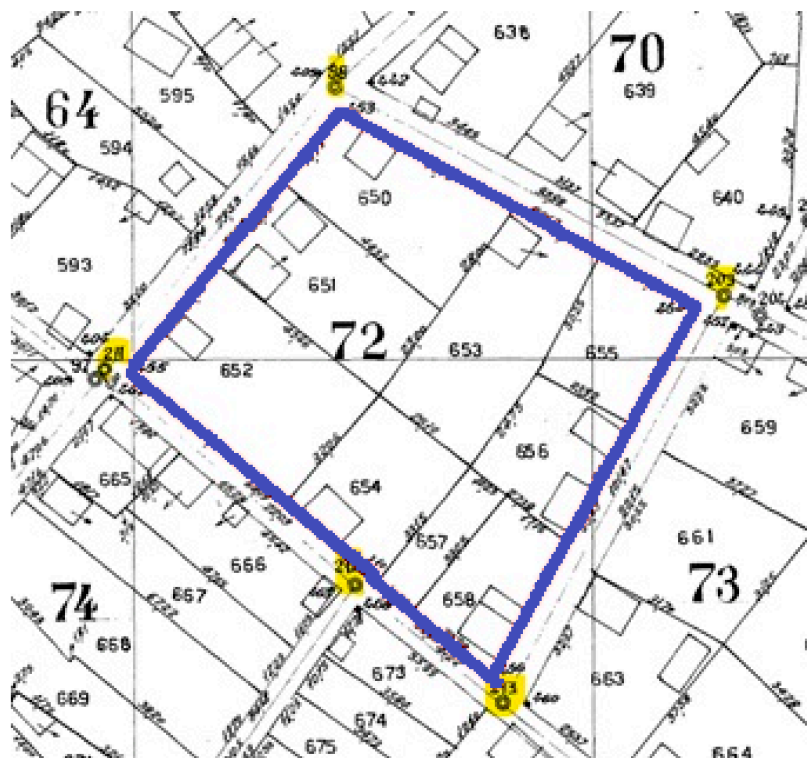


Figure 2. Rural block transformed from OVGRD to HGRS87 (Choristi village, Greece). Boundary coordinates originate from a legacy Old Version of the Greek Datum plan and were transformed to HGRS87 (EPSG:2100). The parcel boundary is highlighted; the underlying plan is reproduced from Hellenic Cadastre records.



Figure 3. Rural parcel transformed from NVGRD to HGRS87 (Nea Amisos village, Greece). Boundary coordinates originate from a New Version of the Greek Datum plan and were transformed to HGRS87 (EPSG:2100). The parcel boundary is highlighted; the underlying plan is reproduced from Hellenic Cadastre records.

Table 3. Summary of parcel area uncertainty estimates (99% confidence level). The configuration term Σd_i^2 is reported so that each propagated value can be verified directly from the table through $\sigma E = \sqrt{0.125 \cdot \sigma_r \cdot \sqrt{(\Sigma d_i^2)}}$, with the confidence multiplier of Equation (8) applied for the interval.

Case	n (Vertices)	Area (m ²)	RMS (m)	Applied Equation	Area Uncertainty (m ²)	Relative Uncertainty (%)	Σd_i^2 (m ²)
Case 1—RTK (HGRS87)	9	134.87	0.10	Equation (10)	2.61	1.9	822
Case 2—OVGRD → HGRS87	6	5547.67	0.17	Equation (11)	31.51	0.6	41,451
Case 3—NVGRD → HGRS87	4	163,636.38	0.15	Equation (12)	244.51	0.2	3,203,995

Table 4. Comparison of parcel area before and after datum transformation (Case 3).

Datum	Area (m ²)
NVGRD (original)	163,764.00
HGRS87 (transformed)	163,636.38
Absolute difference	127.62
Relative difference (%)	0.078

This interpretation can be checked against the systematic term derived above. Treating the difference as a pure scale effect, a linear scale departure of 390 ppm applied to a parcel of 163,636 m² produces an area change of $2E\sigma_s = 2 \times 163,636 \times 390 \times 10^{-6} \approx 127.6$ m², which reproduces the observed difference. The magnitude of the discrepancy is therefore fully accounted for by a scale effect of the size indicated, which supports its treatment as a deterministic datum effect rather than as a realization of random coordinate error. It also illustrates why the two must be kept apart: a scale contribution of this size exceeds the one-standard-deviation random term of 94.9 m² computed for the same parcel, so a transformation whose scale is uncertain at that level would dominate the error budget rather than perturb it.

4.1. Simulation Study

To characterize model behaviour beyond the three illustrative parcels, a controlled synthetic dataset of 460 polygons was generated, spanning compact convex, elongated, and concave or articulated shapes, together with a population of randomly generated irregular parcels of five to sixteen vertices; all were validated as simple polygons free of slivers, spikes, and self-intersections. Relative area uncertainty depends on the parcel shape only through a single dimensionless configuration factor κ , defined as the square root of the sum of squared vertex spacings divided by the parcel area. Varying one factor at a time at fixed area, the configuration term of a regular n-gon equals $8A \cdot \sin(2\pi/n)$, which is maximal for the square and decreases as vertices are added; densifying a boundary with collinear vertices likewise reduces it. Elongation increases the term, a 1:10 rectangle carrying about 2.4 times the uncertainty of a compact parcel of equal area, whereas concavity and articulation do not: across realistic parcel geometries κ occupies a narrow band of about 1.9 to 3.2, and highly articulated boundaries tend to have lower κ . Parcel size is the dominant factor, with the relative uncertainty falling roughly tenfold from a 100 m² lot to a one-hectare parcel (Figure 4). The one-factor controlled experiments behind these findings (vertex count, elongation, and concavity) are shown in Figure 5.

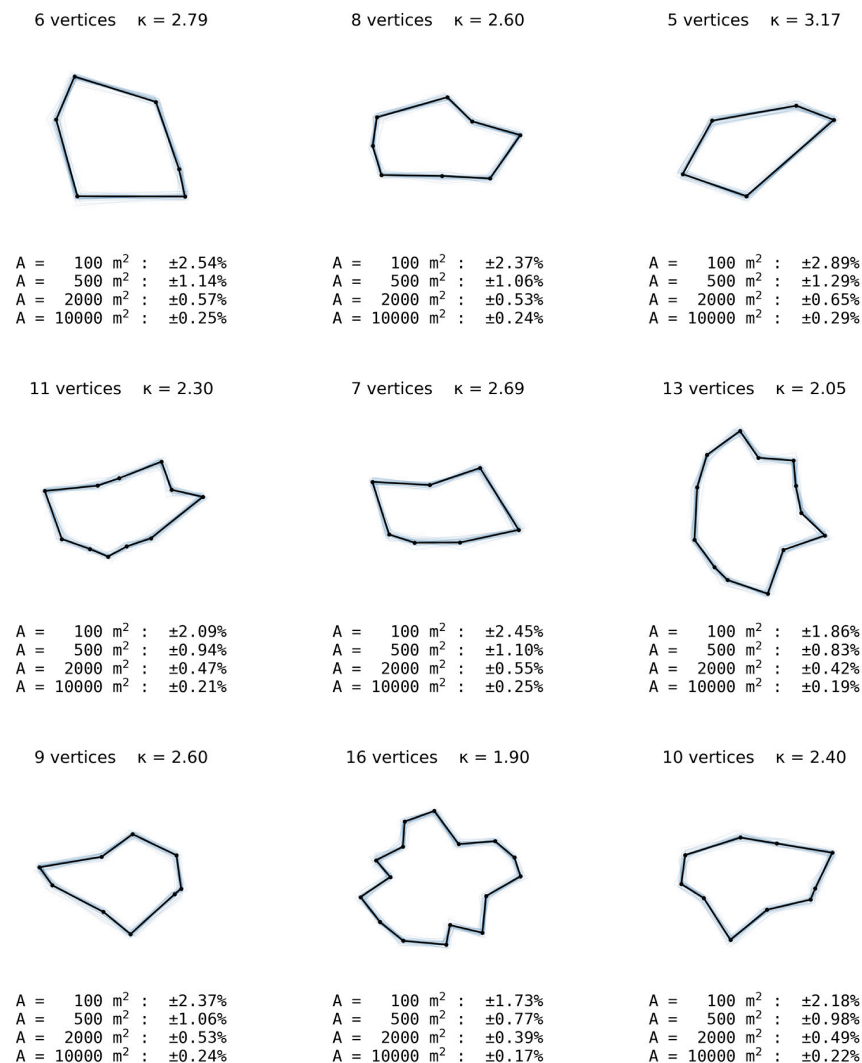


Figure 4. Area uncertainty for natural parcel geometries. Nine irregular cadastral parcels of varying vertex count (five to sixteen), each a validated simple polygon (free of slivers, spikes, and self-intersections) shown with a schematic vertex-perturbation cloud; beneath each parcel the 99% relative area uncertainty is listed for four parcel sizes at a fixed horizontal coordinate uncertainty of 0.10 m. Shape enters the model only through the configuration factor κ , printed for each parcel. Uncertainty is governed by parcel size and only weakly by shape; more articulated boundaries have lower κ , hence lower uncertainty, not higher.

The diagonal model treats every vertex error as independent, which is realistic for a direct field survey but not for a datum transformation, where the errors of neighbouring vertices are correlated. The effect of this simplification was quantified by Monte Carlo simulation. For a suite of fourteen parcel geometries spanning compact, elongated, concave and fingered shapes at two parcel sizes, two hundred thousand realizations of the vertex coordinates were generated under each of five error models, with the injected per-vertex horizontal RMS held equal in every model so that the comparison isolates the correlation structure rather than its magnitude. The models are: independent per-vertex noise, which underlies the closed form; a common translation applied identically to all vertices; a rigid rotation about the parcel centroid; a uniform scale about the centroid; and a spatially correlated residual field with an exponential correlation function whose range equals half the parcel radius of gyration. For each realization the area was recomputed by the Gauss formula and its empirical standard deviation compared with the closed-form value of Equation (7). Under independent noise the simulation reproduced the closed form to

within the sampling error, and a separate test with three million realizations and deliberately unequal Easting and Northing precisions confirmed the anisotropic propagation to within 0.02%.

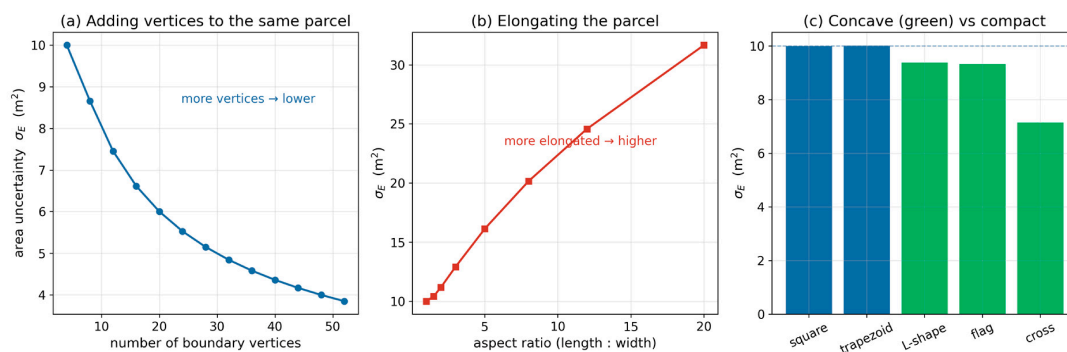


Figure 5. Geometric drivers of area uncertainty, isolated one at a time at equal area and $\sigma_r = 0.10$ m. (a) Adding boundary vertices to a fixed parcel lowers the uncertainty. (b) Elongating the parcel (increasing the aspect ratio) raises it. (c) At equal area, concave parcels (green: L-shape, flag, cross) do not exceed compact ones (blue: square, trapezoid). Dashed line marks the square shape. Among the factors examined, elongation is the one that most clearly increases the area uncertainty.

The results are summarized in Table 5. A common translation and a rigid rotation leave the parcel area exactly unchanged, so their contribution to the area standard deviation is zero irrespective of magnitude; this is the numerical counterpart of the analytical property that the area functional is invariant under rigid-body motion. The remaining components behave differently and, importantly, not in a single direction. Across the geometries examined the ratio of the simulated to the closed-form standard deviation ranged from 0.40 to 3.46 for the uniform-scale model and from 0.59 to 1.29 for the spatially correlated model, exceeding unity for compact parcels and falling below it for strongly elongated ones. The diagonal model therefore cannot be described as a universal upper bound: where the transformation error is dominated by translation and rotation the diagonal treatment overcounts the contribution, whereas where scale uncertainty or spatially structured residuals dominate it can understate the true area uncertainty, particularly for compact parcels. The direction and the magnitude of the approximation error depend jointly on the covariance structure of the transformation and on the parcel geometry, and Table 5 should be read as characterizing that dependence rather than as establishing a bound. Where the scale uncertainty σ_s of a transformation is known, its systematic contribution to the area, $2E\sigma_s$, can be combined in quadrature with the random term of Equation (7); this contribution grows linearly with the parcel area, whereas the random term grows only with the square root of the configuration term.

The stochastic models underlying Table 5 are defined as follows, so that the experiment can be reproduced. Every model injects the same per-vertex horizontal RMS, $\sigma_r = 0.10$ m, so that the comparison isolates the correlation structure rather than its magnitude. The independent model applies uncorrelated Gaussian perturbations with per-component standard deviation $\sigma_r/\sqrt{2}$. The translation model applies a single Gaussian shift, with the same per-component standard deviation, to all vertices simultaneously. The rotation and scale models apply a Gaussian rotation angle and a Gaussian scale factor about the parcel centroid, with standard deviations $\sigma_\theta = (\sigma_r/\sqrt{2})/R$ and $\sigma_s = (\sigma_r/\sqrt{2})/R$ respectively, where R is the radius of gyration of the vertex set; this normalisation makes the root-mean-square displacement of a vertex located at distance R from the centroid equal to the per-component standard deviation of the independent model. The spatially correlated model draws perturbations from a zero-mean Gaussian field with exponential covariance $C_{ij} = (\sigma_r/\sqrt{2})^2$

$\exp(-d_{ij}/L)$ and correlation length $L = R/2$, realised by Cholesky factorisation of the covariance matrix. Each entry is based on 2×10^5 realisations with a fixed random seed.

Table 5. Sensitivity of the propagated area uncertainty to the error-correlation structure. Each model injects the same per-vertex horizontal RMS. Entries are the ratio of the Monte-Carlo area standard deviation to the closed-form value of Equation (7), and are invariant to parcel size. Values above unity indicate that the diagonal model understates the simulated uncertainty; values below unity that it overstates it.

Polygon (Equal Area)	Independent	Translation	Rotation	Scale	Spatial
Square (1:1)	1.00	0.00	0.00	2.00	0.99
Rectangle 1:3	1.00	0.00	0.00	1.20	0.88
Rectangle 1:10	1.00	0.00	0.00	0.40	0.59
Regular hexagon	1.00	0.00	0.00	2.44	1.04
Regular 12-gon	1.00	0.00	0.00	3.46	1.29
L-shaped lot	1.00	0.00	0.00	2.40	1.03
Flag/panhandle lot	1.00	0.00	0.00	2.47	1.03

4.2. Comparison with the Administrative Area-Deviation Rule

To relate the propagated area uncertainty to the indicative administrative screen, the acceptable deviation of Equation (1) was evaluated for the three parcels using the administrative offsets $U_0 = 0.50$ m (urban) and 2.00 m (rural) and the seven-per-cent cap (Table 6). In every case the acceptable deviation exceeds the propagated 99% area confidence interval by roughly an order of magnitude—about 3.6 times for the small urban parcel, twelve times for the medium rural parcel, and at least thirteen times for the large rural parcel—and the margin widens with parcel size. The two measures are therefore consistent rather than contradictory, and the variance-based interval is the tighter, measurement-based indicator, scaling with parcel geometry instead of being fixed at a constant fraction of the area. These margins should nevertheless be read together with the correlation analysis of Section 4.1. The confidence intervals in Table 6 are those of the diagonal, independent model, which for compact parcels may understate the uncertainty arising from a correlated transformation error by a factor of up to about 3.5. Applying such a factor would leave the margin for the two rural parcels intact but would substantially reduce, and in the limiting case remove, the margin of roughly 3.6 for the small urban parcel. The comparison therefore establishes that the two measures are of compatible magnitude rather than that the stochastic interval is uniformly the smaller of the two. In this sense the stochastic estimate complements the administrative rule and is consistent with the coordinate-accuracy framework applied in practice.

Table 6. Comparison of the indicative administrative acceptable area deviation (Equation (1)) with the propagated area confidence intervals, per case. $U_0 = 0.50$ m (urban) and 2.00 m (rural); the seven-per-cent cap binds for Cases 1 and 2. For Case 3 the deviation is shown for a compact parcel shape ($P/P_t = 1$) and increases with perimeter up to the seven-per-cent cap of 11,455 m².

Case	E (m ²)	Zone	A _{tol} (m ²)	$\sigma_E, 1\sigma$ (m ²)	95% Half-Width (m ²)	99% Half-Width (m ²)	A _{tol} /99% Half-Width
Case 1—Drama	134.87	urban	9.4	1.01	1.99	2.61	3.6
Case 2—Choristi	5547.67	rural	388.3	12.23	23.98	31.51	12.3
Case 3—N. Amisos	163,636.38	rural	3252	94.9	186.0	244.51	13.3

Table 6 compares two thresholds rather than validating the model against observed discrepancies. Registered title areas were not available for the three parcels, so the observed difference between a registered and a measured area, and the associated pass or fail decision under the administrative rule, cannot be reported here. The only area difference available

in the present material is the 127.62 m² difference of Case 3, which arises from the datum transformation and is deterministic in origin, and which for that reason is not interpreted through the stochastic confidence interval. A validation against observed discrepancies would require a sample of parcels for which both the registered and the newly measured areas are available, and this remains an objective for further work.

5. Discussion

5.1. Pathways Towards Implementation

Introducing parcel-level area uncertainty into Greek cadastral practice does not require institutional redesign. The mathematical basis and necessary stochastic inputs are already available through RTK specifications and officially reported transformation RMS values. The essential change concerns formalization and recording.

The first step is to compute area variance using the simplified propagation formula under explicit assumptions. Where full covariance matrices are unavailable, a diagonal approximation and a common horizontal standard deviation per vertex can be used. For RTK-derived parcels, the relevant term combines field precision with the operational transformation RMS. For legacy transformations, the published RMS of the datum conversion becomes the dominant parameter. These transformation characteristics are already documented in Greek geodetic literature [11,29,33].

The second step is to retain existing deterministic acceptance rules while supplementing them with statistical reporting. The equivalent-square tolerance formula, where it applies, can continue to serve as an indicative administrative screen. The proposed method adds a parcel-specific confidence interval derived from coordinate precision, allowing uncertainty to be computed and documented in a transparent and auditable manner [5,25]. This fact addresses concerns that variance-based approaches are too strict or complex: the stochastic result informs interpretation and dispute assessment, without altering acceptance thresholds.

Finally, we need to consider provenance. Parcels derived from RTK surveys or legacy transformations should carry an indicator of their measurement pathway and the RMS term used in propagation. Recording this information aligns with structured geospatial quality reporting practices [34] and enables differentiation between upgraded and transformation-dominated geometries over time.

Adoption is justified by proportionality and comparability. Reported uncertainty ratios range from about 0.2% to 2% depending on parcel size and origin. While numerically modest, these differences translate into measurable land areas that may affect urban contributions or rural consolidation units. Cadastral practice already references shape-aware tolerance formulas. The proposed framework makes the statistical basis explicit and improves interpretability in administrative and judicial contexts [5].

The method is transferable to jurisdictions with mixed legacy coordinate systems and ongoing GNSS-based modernization, including parts of Southern and Eastern Europe where historic datums coexist with national reference frames. In such settings, transformation RMS values are documented but parcel-level uncertainty is rarely propagated. The framework offers a scalable way to connect available precision metrics with areal reliability, without requiring full covariance reporting.

5.2. Methodological Reflections and Future Research

The proposed formulation rests on three assumptions: diagonal covariance, equal horizontal precision in Easting and Northing, and a common standard deviation for all parcel vertices. These reflect typical information available in Greek cadastral prac-

tice, where survey reports or transformation documentation often provide only a single RMS value.

The diagonal covariance assumption omits correlation terms between coordinate components and between neighboring vertices. In fully adjusted networks, such correlations may influence propagated area variance. Where complete variance–covariance matrices are available, the same Jacobian framework can incorporate them directly. The present version should therefore be read as a reduced form suited to limited covariance reporting.

Assuming equal Easting and Northing precision suppresses possible anisotropy in transformation residuals. Using a single RMS value, such as 8.3 cm for HTRS07 to HGRS87 or higher RMS values for OVGRD and NVGRD transformations, applies a uniform stochastic term across space. This is acceptable for national comparison, but less precise for local diagnostics. A logical extension would introduce region-specific or gridded transformation accuracy models.

The assumption of common uncertainty for all vertices simplifies mixed-provenance parcels. In practice, some vertices may derive from RTK surveys and others from transformed legacy plans. A refined formulation could assign vertex-specific standard deviations and propagate them individually. The examples confirm two structural properties of the model. Absolute area uncertainty increases with parcel size and the spatial spread of the boundary (elongation), not with the number of vertices; densely spaced or collinear vertices do not increase the configuration term and can reduce it. Relative uncertainty decreases as area grows: approximately 2% for a small urban RTK parcel, 0.6% for a medium rural parcel transformed from OVGRD, and 0.2% for a large consolidation unit. The variance depends on both coordinate precision and parcel geometry. Elongated parcels produce larger configuration terms than compact parcels of equal area, whereas concave or articulated parcels do not do so systematically; the governing quantity is the spatial configuration of the vertices rather than the number of vertices or the presence of concavity.

Future research should test the approximation against full variance–covariance propagation for parcels where complete adjustment reports are available, in order to quantify the effect of the simplifying assumptions. It should also examine the impact of replacing national RMS values with regional or grid-based transformation residual statistics, allowing parcel-level uncertainty to vary geographically rather than remain uniform [34]. A further extension would assign vertex-specific standard deviations in mixed-provenance geometries, reflecting heterogeneous survey lineage within a single parcel. Finally, systematic analysis of subdivision and land readjustment cases could clarify how increasing vertex count and geometric fragmentation influence propagated area uncertainty in practice.

5.3. Impact on Urban Planning and Land Administration

Cadastral geometry constitutes the spatial substrate of statutory planning in Greece. Local Urban Plans under the Constantinos Doxiadis Programme are prepared and implemented on the basis of parcel boundaries and areas recorded in HGRS87/HTRS07 [35]. Building regulations, design codes, compulsory purchase, value capture and land readjustment mechanisms all refer to cadastral units (plots) as their reference geometry. The reliability of planning outcomes therefore depends on the geometric reliability of parcel coordinates and the accuracy of the areas derived from them [36].

A central mechanism in Greek urban development is the land and money contribution system established by Law 1337/1983 and subsequent updates. During implementation of an urban layout plan, each owner contributes a percentage of the initial parcel area to secure public space and infrastructure. Even modest area discrepancies may alter calculated contributions or compensation. Current practice evaluates such differences

through deterministic tolerance bands. These bands support administrative screening but do not express statistical confidence in the registered area [37–39].

The proposed uncertainty propagation model introduces an explicit link between coordinate precision and area reliability. For planning authorities, this provides a quantitative basis for assessing whether observed area differences are consistent with measurement uncertainty or suggest substantive boundary change. In land readjustment projects, where parcels are subdivided and reshaped, the model clarifies how the resulting changes in parcel geometry affect propagated area variance. This is relevant for minimum lot size requirements and proportional contribution calculations embedded in planning legislation.

The approach also aligns with the digital transformation of spatial governance in the European Union. Under the INSPIRE Directive, cadastral parcels constitute a core spatial data theme, and Member States are required to publish interoperable datasets with documented quality elements. Although ISO 19157 defines the structure for reporting positional accuracy, it is INSPIRE that frames the practical obligation for harmonized metadata and cross-border comparability. Recording parcel-level area uncertainty as a documented quality measure would strengthen the consistency between cadastral and planning layers and improve traceability in automated planning workflows.

6. Conclusions

This study introduces a first-order linearized model, assuming diagonal covariance and equal coordinate variances, to translate coordinate uncertainty into parcel area uncertainty in the Greek cadastre. Using the Gauss area function and simplified covariance assumptions, the model links RTK precision and transformation RMS values to parcel-specific confidence intervals. The results show that absolute area uncertainty increases with parcel size and boundary elongation, while relative uncertainty typically decreases; it is governed by the spatial spread of the vertices rather than their number. A Monte Carlo analysis of the error-correlation structure further shows that the diagonal model is not a universal bound on the true area uncertainty: the common translation and rotation components of a datum transformation leave the area unchanged, whereas scale and spatially correlated residuals may raise the true uncertainty above the diagonal estimate, particularly for compact parcels. The approach does not replace existing deterministic tolerance rules; it makes their stochastic basis explicit and measurable.

The proposed method is technically consistent with established error propagation theory and compatible with current Greek reference systems and workflows. It supports more transparent interpretation of area differences in planning, land readjustment, and dispute contexts, while remaining feasible under limited covariance reporting. Beyond Greece, the framework is transferable to cadastral systems that combine legacy transformations with GNSS-based modernization, offering a scalable means to document parcel-level geometric reliability without structural reform.

The proposed formulation is an approximate model. It assumes a diagonal covariance matrix, equal Easting and Northing precision, uniform vertex precision, approximately Gaussian coordinate errors, and nationally averaged RMS values; within these assumptions the simulation study indicates that area uncertainty is governed primarily by parcel size and secondarily by boundary elongation, and is essentially insensitive to boundary complexity or vertex count. The independence assumption in particular should be understood as a working approximation whose error is characterized in Section 4.1 rather than bounded, and confidence intervals computed under it should be interpreted with that in mind where a transformation is the dominant error source. Accordingly, the administrative, judicial, and planning uses discussed here should be read as potential applications rather than validated outcomes. For planning and permitting authorities, a practical recommendation

follows: the parcel-level area uncertainty, expressed in square metres at a stated confidence level, can be recorded alongside the existing tolerance screening and used to judge whether an observed area difference is compatible with measurement uncertainty before it triggers correction, compensation, or dispute.

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References

1. Fys, M.; Hubar, Y.; Brydun, A.; Sohor, A. Comparison and accuracy of the methods for determining the area of parcels. *Tech. Sci. Technol.* **2023**, *2*, 363–378. [\[CrossRef\]](#)
2. Yildiz, U.; Gürel, M.; Kocaman, S. State liability and uncertainty perception on cadastral parcel area registry in Turkey. *Land Use Policy* **2022**, *116*, 106075. [\[CrossRef\]](#)
3. Degel, B. Reliability aspects of the German cadastre. *Z. Geodäsie Geoinf. Landmanag.* **2019**, *144*, 373–380.
4. Hagemans, E. The new, LADM inspired, data model of the Dutch cadastral map. *Land Use Policy* **2022**, *117*, 106074. [\[CrossRef\]](#)
5. RICS. *Boundaries: Procedures for Boundary Identification, Demarcation and Dispute Resolution*, 4th ed.; Royal Institution of Chartered Surveyors: London, UK, 2021.
6. Tong, X.; Shi, W.; Liu, D. Introducing scale parameters for adjusting area objects in GIS based on least squares and variance component estimation. *Int. J. Geogr. Inf. Sci.* **2009**, *23*, 1413–1432. [\[CrossRef\]](#)
7. Sisman, Y. Coordinate transformation of cadastral maps using different adjustment methods. *J. Chin. Inst. Eng.* **2014**, *37*, 869–882. [\[CrossRef\]](#)
8. Iliffe, J. *Datums and Map Projections for Remote Sensing, GIS, and Surveying*; Whittles Publishing: Caithness, UK, 2000. Available online: https://archive.org/details/datumsmapproject0000ilif_m2u9 (accessed on 20 May 2026).
9. Drobež, P.; Fras, M.K.; Ferlan, M.; Lisec, A. Transition from 2D to 3D real property cadastre: The case of the Slovenian cadastre. *Comput. Environ. Urban Syst.* **2017**, *62*, 125–135. [\[CrossRef\]](#)
10. Van Oosterom, P.J.M.; Lemmen, C.H.J.; Ingvarsson, T.; Van der Molen, P.; Ploeger, H.; Zevenbergen, J. The core cadastral domain model. *Comput. Environ. Urban Syst.* **2006**, *30*, 627–660. [\[CrossRef\]](#)
11. Katsambalos, K.; Kotsakis, C.; Gianniou, M. Hellenic terrestrial reference system 2007 (HTRS07): A regional realization of ETRS89 over Greece in support of HEPOS. *Bull. Geod. Geomat.* **2010**, *69*, 151–164.
12. HM Land Registry. HM Land Registry Plans: Boundaries (Practice Guide 40, Supplement 3). Available online: <https://www.gov.uk/government/publications/land-registry-plans-boundaries/land-registry-plans-boundaries-practice-guide-40-supplement-3> (accessed on 9 March 2020).
13. Swiss Confederation. *Verordnung über die amtliche Vermessung (VAV)*, SR 211.432.2, and *Technische Verordnung des VBS über die amtliche Vermessung (TVAV)*, SR 211.432.21; Federal Office of Topography (Swisstopo): Wabern, Switzerland, 2024. Available online: <https://www.fedlex.admin.ch> (accessed on 20 July 2026).
14. Navratil, G.; Hafner, J.; Jilin, D. Accuracy determination for the Austrian Digital Cadastral Map (DKM). In *Proceedings of the Fourth Croatian Congress on Cadastre, Zagreb, Croatia*; Croatia Geodetic Society: Zagreb, Croatia, 2010; pp. 171–176.
15. Hoogmoed, M.; Van Oosterom, P.; Hagemans, E. Visualizing the difference between the geometric and administrative surface area of the Cadastral Map of the Netherlands. In *Proceedings of the FIG Commission 7 & 2 Annual Meeting 2023*, Deventer, The Netherlands, 2–4 October 2023.
16. Paunescu, C.; Mihalcea, V.; Paunescu, V. Considerations regarding the accuracy of determination of surfaces. In *Proceedings of the FIG Congress 2022*, Warsaw, Poland, 11–15 September 2022.

17. Yildiz, O. Cadastral map data quality in Turkey and methods used to increase data quality. In Proceedings of the FIG Working Week 2020, Amsterdam, The Netherlands, 10–14 May 2020.
18. AdV (Arbeitsgemeinschaft der Vermessungsverwaltungen). Real Estate Cadastre (ALKIS). Available online: <https://www.adv-online.de/Products/Real-Estate-Cadastre/> (accessed on 1 February 2026).
19. Ministerium für Landesentwicklung und Wohnen Baden-Württemberg. *Verwaltungsvorschrift für die Durchführung von Liegenschaftsvermessungen (LV-Vorschrift—VwVLV) vom 12. April 2022*; GABl. as Amended 7 December 2023; Landesamt für Geoinformation und Landentwicklung Baden-Württemberg: Stuttgart, Germany, 2022; p. 354.
20. Republic of Austria. *Bundesgesetz vom 3. Juli 1968 über die Landesvermessung und den Grenzkataster (Vermessungsgesetz—VermG)*; BGBl. Nr. 306/1968, as last amended by BGBl. I Nr. 116/2022; Rechtsinformationssystem des Bundes (RIS): Vienna, Austria, 1968.
21. Pullar, D. Accuracy issues for spatial update of digital cadastral maps. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 221. [CrossRef]
22. Polman, J.; Salzmann, M.A. (Eds.) *Handleiding Voor de Technische Werkzaamheden van Het Kadaster (HTW 1996)*; Dienst van het Kadaster en de Openbare Registers: Apeldoorn, The Netherlands, 1996; ISBN 90-803078-1-5.
23. Agenția Națională de Cadastru și Publicitate Imobiliară. *Ordin nr. 979/2016 Privind Aprobarea Specificațiilor Tehnice de Realizare a Lucrărilor Sistemice de Cadastru pe Sectoare Cadastrale*; Monitorul Oficial al României, Partea I, nr. 636 and 636 bis, 18 August 2016; Agenția Națională de Cadastru și Publicitate Imobiliară: Bucharest, Romania, 2016.
24. Ministerio de la Presidencia. *Resolución de 29 de Octubre de 2015, de la Subsecretaría, por la que se Publica la Resolución Conjunta de la Dirección General de los Registros y del Notariado y de la Dirección General del Catastro, por la que se Regulan los Requisitos Técnicos Para el Intercambio de Información Entre el Catastro y los Registros de la Propiedad*; BOE-A-2015-11655; Boletín Oficial del Estado: Madrid, Spain, 2015.
25. Republic of Türkiye. *Büyük Ölçekli Harita ve Harita Bilgileri Üretim Yönetmeliği (Regulation on the Production of Large-Scale Maps and Map Information)*; Decision No. 2018/11962; Resmi Gazete No. 30460 (Mükerrer), 26 June 2018; Republic of Türkiye: Ankara, Türkiye, 2018.
26. IGN. *Plan Cadastral Numérique—Recommandations Techniques*; Institut National de l'Information Géographique et Forestière: Saint-Mandé, France, 2019. Available online: <https://bofip.impots.gouv.fr/bofip/10848-PGP.html/identifiant%3DACTU-2019-00203> (accessed on 28 July 2026).
27. DGFIP. *Spécifications Techniques du Plan Cadastral Informatisé (PCI Vecteur)*; Direction Générale des Finances Publiques: Paris, France, 2020. Available online: <https://cadastre.data.gouv.fr/datasets/plan-cadastral-informatise> (accessed on 28 July 2026).
28. IGN. *Guide de Remaniement Cadastral*; Institut National de l'Information Géographique et Forestière: Paris, France, 2021. Available online: <https://www.collectivites-locales.gouv.fr/animer-les-territoires/environnement-et-urbanisme/le-cadastre/les-chantiers-de-modernisation-du-plan-cadastral> (accessed on 28 July 2026).
29. Ministero delle Finanze (Italy). *Circolare n. 2/1988 e Successive Circolari (Circolare 5/1989; Circolare 2/1992) Sulle Tolleranze Catastali*; Ministero delle Finanze: Rome, Italy, 1988.
30. Mora-Navarro, G.; Femenia-Ribera, C.; Velilla Torres, J.M.; Martinez-Llario, J. Geographical Data and Metadata on Land Administration in Spain. *Land* **2022**, *11*, 1107. [CrossRef]
31. ISO 19157:2013; Geographic Information—Data Quality. International Organization for Standardization: Geneva, Switzerland, 2013.
32. ISO 2859-2:2020; Sampling procedures for inspection by attributes—Part 2: Sampling plans indexed by limiting quality (LQ) for isolated lot inspection. International Organization for Standardization: Geneva, Switzerland, 2020.
33. Kavadas, I. Forming a quality model for cadastral data using international standards. In Proceedings of the EuroGeographics SDQ 2018 Workshop, Valletta, Malta, 6 February 2018. Available online: https://eurogeographics.org/app/uploads/2025/09/12-Ioannis_Kavadas.pdf (accessed on 20 May 2026).
34. Veis, G. National Report of Greece. In Proceedings of the Symposium of the IAG Subcommission for the European Reference Frame (EUREF), Ankara, Turkey, 22–25 May 1996; Verlag der Bayerischen Akademie der Wissenschaften: Munich, Germany, 1996.
35. Ampatzidis, D.; Melachroinos, S. The connection of an old geodetic datum with a new one using Least Squares Collocation: The Greek case. *Contrib. Geophys. Geod.* **2017**, *47*, 39–51. [CrossRef]
36. Hellenic Mapping and Cadastral Organization (HEMCO). *Tables of Coefficients for Coordinates Transformation of the Hellenic Area*; HEMCO: Athens, Greece, 1995. (In Greek)
37. Ampatzidis, D.; Perperidou, D.G.C.; Vartholomaios, A.; Demirtzoglou, N.; Moschopoulos, G. The Local Area Distortion Factor (LADF): Resolving property area and spatial deviations from geodetic transformations in the Greek cadastre. *Land* **2025**, *14*, 1071. [CrossRef]
38. Takos, I. New adjustment of Greek geodetic networks. *J. Hell. Mil. Geogr. Serv.* **1989**, *36*, 15–30. (In Greek)
39. Ampatzidis, D.; Demirtzoglou, N. The evaluation of the transformation model of the 3-D information between HTRS07 (Hellenic Terrestrial Reference System 2007) and HGRS87 (Hellenic Geodetic Reference System 1987) at the area of Drama. *Acta Montan. Slovaca* **2017**, *22*, 172–179.

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