Revista Brasileira de Cartografia
ISSN 1808-0936 | https://doi.org/10.14393/revbrascartogr
Sociedade Brasileira de Cartografia, Geodésia, Fotogrametria e Sensoriamento Remoto

ITACaRT: An Equal-Area Parallelogram Discrete Global Grid System for Terrestrial Cadastral Mapping—Designed for Usability and Blockchain Integration

ITACaRT: Um Sistema de Grade Global Discreta de Paralelogramo de Áreas Iguais para Mapeamento Cadastral Terrestre — Projetado para Usabilidade e Integração com Blockchain

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Recebido: 08.2025 | Aceito: 10.2025

Abstract: Typically, the modernization of Land Administration Systems (LAS) concentrates on overarching aspects and seldom investigates the spatial infrastructure that underpins it, thereby presenting challenges for the integration of geospatial data. For this purpose, Discrete Global Grid Systems (DGGS), characterized by its "congruent cartography", offer a promising solution within a multi-scale reference framework. Moreover, a significant gap exists in the absence of a DGGS designed to address the cartographic focus and usability requirements for land administration, such as equal-area sizing and geodetic precision. Developed at the Aeronautics Institute of Technology (ITA), the ITA Cadastral Ellipsoidal Reference Tessellation (ITACaRT) was introduced as an innovative DGGS to bridge this gap. The development of ITACaRT was guided by several key criteria, including its suitability for cadastral purposes at appropriate scales, compatibility with the WGS84 ellipsoid and Global Navigation Satellite Systems (GNSS), utilization of simple parallelogram-shaped equal-area cells, a direct tessellation adhering to Cartesian geometry for usability by geoinformation professionals, and decimal convergence to facilitate blockchain tokenization. Complementary to these criteria, a Compositional Hierarchical Indexing system was devised to represent cadastral vector features more efficiently than the atomic identifiers typical of conventional DGGS. ITACaRT thus establishes a solid foundation for contemporary LAS, providing a viable spatial infrastructure that supports emerging technologies such as blockchain.
Keywords: Discrete Global Grid Systems. Cadastral Mapping. Hierarchical Indexing. Blockchain.

Resumo: Normalmente, a modernização dos Sistemas de Administração Territorial (LAS) concentra-se em aspectos abrangentes e raramente investiga a infraestrutura espacial que a sustenta, o que apresenta desafios para a integração de dados geoespaciais. Para este fim, os Sistemas de Grades Globais Discretas (DGGS), caracterizados por sua "cartografia congruente", oferecem uma solução promissora dentro de um quadro de referência multiescalar. No entanto, existe uma lacuna significativa na ausência de um DGGS projetado para atender ao foco cartográfico e aos requisitos de usabilidade para a administração de terras, como a isometria de área e a precisão geodésica. Desenvolvido no Instituto Tecnológico de Aeronáutica (ITA), o ITACaRT (ITA Cadastral Ellipsoidal Reference Tessellation) foi introduzido como um DGGS inovador para preencher essa lacuna. O desenvolvimento do ITACaRT foi guiado por vários critérios-chave, incluindo sua adequação para fins cadastrais em escalas apropriadas, compatibilidade com o elipsoide WGS84 e Sistemas Globais de Navegação por Satélite (GNSS), utilização de células simples de área igual em forma de paralelogramo, uma tesselação direta aderente à geometria cartesiana para usabilidade por profissionais de geoinformação e convergência decimal para facilitar a tokenização em blockchain. Complementar a esses critérios, foi concebido um sistema de Indexação Hierárquica Composicional para representar feições vetoriais cadastrais de forma mais eficiente do que os identificadores atômicos típicos dos DGGS convencionais. O ITACaRT estabelece, assim, uma base sólida para os LAS contemporâneos, fornecendo uma infraestrutura espacial viável que suporta tecnologias emergentes como o blockchain.
Palavras Chave: Sistemas de Grade Global Discreta. Mapeamento Cadastral. Indexação Hierárquica. Blockchain.

1 INTRODUCTION

Cadastral mapping is a fundamental part of Land Administration Systems (LAS). It provides precise definitions of property boundaries and establishes the foundation for legal ownership, taxation, and urban planning. In the LAS framework, cadastral systems and Land Information Systems are integrated into the Spatial Data Infrastructure (SDI), which encompasses elemental spatial data, integration standards, distribution networks, and related policies (Williamson et al., 2010). The success of an SDI largely depends on the ability to integrate and manage these spatial records effectively.

However, as geoinformation technologies advance, the limitations of the traditional approach become more apparent. The need for more scalable and interoperable methods grows stronger. The conventional Geographic Information System (GIS) structure, based on isolated thematic layers, presents significant obstacles to integrating data from multiple sources. Combining vector parcel data with elevation models or satellite imagery, for instance, remains a complicated challenge, preventing the development of a unified and consistent reference system. This absence of a "congruent geography", as highlighted by Goodchild (2018), results in unintegrated data that obstructs comprehensive analysis and limits the scalability needed to manage the volume and diversity of geospatial data available today. This underscores the necessity for a new paradigm for organizing spatial data, especially for modern cadastres.

Faced with these challenges, Discrete Global Grid Systems (DGGS) emerge as a diverse approach, providing a unified and inherently multi-scale reference framework. Although they present a theoretical solution to integration and scalability issues, their use in the cadastral domain remains mostly unexplored. The focus on modernizing LAS, as exemplified by the work of Rajabifard (2019), is often on performance evaluation frameworks, data interoperability, and process digitalization, but rarely questions or suggests restructuring the underlying spatial reference system, which is the root of many challenges.

Furthermore, the most prominent DGGS implementations, such as Uber’s H3 and Google’s S2, were developed, respectively, to solve web-scale logistics and indexing challenges, focusing on topology or computational speed rather than non-negotiable properties for cadastres, such as the preservation of equal areas and geodetic accuracy. As a result, a noticeable gap exists in the literature for a DGGS specifically designed to meet the cartographic precision and legal certainty needed for land administration, creating an opportunity for a truly innovative contribution in this field.

To address this gap, we introduce the ITA Cadastral Ellipsoidal Reference Tessellation (ITACaRT), developed at the Aeronautics Institute of Technology (ITA), a novel DGGS explicitly designed to overcome the identified limitations. Unlike existing solutions, ITACaRT improves accuracy by using a direct tessellation on the WGS84 ellipsoid instead of a simplified sphere, ensuring geodetic fidelity. It meets the legal requirement of cadastral land use through an equal-area projection, so each parallelogram cell represents the same area on Earth’s surface. Additionally, ITACaRT’s design emphasizes usability by incorporating principles that approximate a Cartesian system, aiming for adoption by geoinformation professionals. Furthermore, it is intended to serve as the spatial infrastructure for integrating blockchain technologies to create secure, immutable land tenure records, with a theoretical approach for tokenizing its cells. This is facilitated by a compositional indexing method, an innovation that distinguishes ITACaRT from other DGGS.

The objective of this article, therefore, is to present the complete conceptual methodology of ITACaRT, validating it as a contribution to the evolution of modern Territorial Administration Systems.

This paper is an extended version of the work previously developed by Silva et al. (2025), presented at the XXV Brazilian Symposium on GeoInformatics (GeoInfo 2025), and is organized as follows. Section 2 reviews the current state of the art in DGGS and relevant topics related to this work. Section 3 describes the methodology and design of ITACaRT, including a detailed study of its grid behavior and neighborhood relations. Section 4 discusses the system’s properties, including a qualitative analysis of angular distortion and its compliance with Open Geospatial Consortium (OGC) standards. Finally, Section 5 provides the conclusion and suggestions for future research.

2 BACKGROUND

This section provides a review of the current advancements in DGGS to contextualize the development of ITACaRT. The analysis includes the definition of the DGGS paradigm and its role within the Digital Earth vision, examines the fundamental properties and design trade-offs of the technology, analyzes work directly related to the ITACaRT architecture, and concludes with the identification of a research gap for a system dedicated to cadastral applications.

2.1 DGGS Context

A DGGS, as formally defined by the OGC under the ISO 19170 series, constitutes a spatial reference system that uses a hierarchical tessellation of cells to partition and address the globe (Gibb, 2021). In essence, it is a system that provides a discrete representation of the Earth utilizing a global grid composed of geometric cells (Sahr et al., 2003).

This approach signifies a paradigm shift from traditional Coordinate Reference Systems (CRS). While CRS are primarily devised for navigation and point localization, a DGGS is designed as an informational framework intended to ensure consistent visualization and reproducible measurements within specific regions of the Earth's surface. This transition illustrates a shift in focus from the map to the cells. According to Li and Stefanakis (2020), DGGS, with its cell-centered methodology, has the potential to surpass traditional GIS, which are characterized by segmented informational layers, to a certain extent.

This concatenation of layers within a unified framework of "congruent geography", as described by Goodchild (2018), can establish the foundational basis for Digital Earth, given its necessity for uniformity (Goodchild et al., 2012). Indeed, according to Mahdavi-Amiri et al. (2015), the discretization of the Earth constitutes the backbone of Digital Earth, which advocates for a three-dimensional, multiresolution representation of the planet.

2.2 Geometries and Fundamental Properties in DGGS

A DGGS architecture can be characterized by a series of design decisions, among which the selection of the cell's geometry constitutes a primary consideration. Three fundamental cell shapes—commonly employed quadrilaterals, computationally efficient triangles, and highly regular hexagons—impart distinctive characteristics to the structure of a DGGS, each presenting its own set of advantages and disadvantages (Peterson et al., 2015). The choice of cell shape involves balancing geodetic fidelity, topological consistency, and hierarchical congruency, thereby creating a design trilemma. Although the term 'trilemma' is not explicitly defined within the literature, the underlying concept can be inferred from the trade-offs discussed by various authors. For instance, the analysis conducted by Bondaruk et al. (2020) demonstrates that hexagons exhibit high topological regularity owing to their uniform adjacency, but this comes at the expense of hierarchical congruency—as they cannot be subdivided perfectly. Consequently, the same analysis reveals that quadrilaterals and triangles provide perfect hierarchical congruency but relinquish topological regularity, demonstrating non-uniform adjacency with their neighboring units.

Specifically for quantitative applications, such as cadastral mapping, the equal-area property guarantees that each cell at a specified resolution level corresponds to an identical area on the Earth's surface. This ensures that statistical comparisons, including the density of phenomena, are free from bias introduced by variations in the unit of analysis size. In the context of cadastral mapping, where parcel area constitutes a fundamental legal and economic attribute utilized for taxation and valuation purposes, this property is indispensable. The significance of this principle is formally recognized in the OGC specification (Gibb, 2021), which dedicates a specialization to "Equal-Area Earth Reference System."

For precise visualizations and analyses, a significant challenge lies in correlating DGGS resolutions with the conceptions of cartographic scales. In this study, visualization scales are determined based on the minimum visible line on paper maps, set at 0.1 millimeters as proposed by Jenny et al. (2008), where DGGS resolutions may have sizes and scales characterized by perceptible line features. Alternatively, analysis scales can be derived from sampling theory, as articulated by Tobler (1987), using the formula: $scale = resolution * 2 * 1000$, which facilitates the calculation of the appropriate map scale corresponding to a given data resolution. These relationships ensure that the resolution of a DGGS is sufficient not only for data storage but also for analysis and visualization at scales perceivable and useful to humans.

2.3 Related Work

The design of a DGGS can be accomplished through two distinct tessellation methods: the projected polyhedral approach, which is the predominant technique, or the direct surface approach (Kimerling et al., 1999). The former employs a reference polyhedron, such as a cube or an icosahedron, projected onto the Earth's surface. While this method is effective for generating grids with cells of uniform shape and area—such as triangles or hexagons—it may introduce layers of abstraction and projection distortions (White et al., 1998). In contrast, direct surface tessellation constructs the grid directly on the reference sphere or ellipsoid, emphasizing geodetic accuracy, though it incurs higher computational demands. The subsequent work concentrates on implementations that, similar to ITACaRT, endorse this alternative philosophy.

Zhou et al. (2007) introduced an approach for direct tessellation, referred to as the "direct partition method", which employs an equal-area projection known as the "parallels plane projection." This projection is the sinusoidal projection in the ellipsoidal reference. Indeed, if the ellipsoidal parameters in the equations are replaced by spherical parameters (where eccentricity $e = 0$), the formulas simplify to the classic spherical sinusoidal projection as detailed in Snyder (1987). The core of their methodology is defined by the Eq. (1) and (2), which transform geographic coordinates (λ, ϕ) into Cartesian coordinates (x, y), taking into account the semi-major axis a and the first eccentricity e of the ellipsoid.

$$x = f_1(\lambda, \phi) = \lambda \frac{a \cos \phi}{\sqrt{1 - e^2 \sin^2 \phi}} \tag{1}$$

$$y = f_2(\phi) = \int_0^{\phi} \frac{a\left(1 - e^2\right)}{\left(1 - e^2 \sin^2 \Phi\right)^{3/2}} \, d\Phi \tag{2}$$

Based on this projection, Ma et al. (2009) proposed a DGGS that employs square, congruent cells within the projected plane. While this implementation marked progress by utilizing square cells in a projection, the sinusoidal properties induce substantial angular distortion in cells on the ellipsoid, particularly at higher latitudes and longitudes. This shape distortion poses a limitation for applications demanding high geometric accuracy, such as cadastral surveys, thereby prompting the exploration of approaches aimed at mitigating this effect. Furthermore, the considerable variation in cell shape across the globe leads to a potential misalignment between different resolution levels on the ellipsoid, a problem less pronounced in polyhedral-based grids, which diminishes the advantage of hierarchical systems.

2.4 The Gap in Literature

The modernization of LAS is a recurring theme, driven by the necessity to address challenges such as urbanization, sustainable development, and the legal security of land tenure (Williamson et al., 2010). However, discussions on the modernization of LAS, such as those presented in Rajabifard (2019) and Yomralioglu and McLaughlin (2017), tend to focus on performance evaluation frameworks, process digitalization, and data interoperability within institutional contexts. These initiatives rarely examine the SDI framework supporting these systems. This deficiency in focus is especially troubling considering that this infrastructure is characterized as "the engine of the entire LAS" (Dawidowicz & Źróbek, 2017), and that guaranteeing its integrity continues to be "one of the major challenges" for any contemporary spatial data initiative (Cooper et al., 2014). This underscores a notable deficiency in discourse regarding the spatial framework underlying these systems, representing a significant gap in academic research, particularly concerning data integration and the scalability of LAS-related databases.

This deficiency becomes evident when critically examining existing DGGS implementations, none of which are appropriately fitted to meet the requirements of cadastral mapping. Prominent DGGS implementations, such as Uber's H3 for marketplace analytics or Google's S2 for global database indexing, primarily emphasize topological regularity (H3 hexagons) or computational efficiency (S2 squares). Other systems, including GEOSOT (Cheng et al., 2016), focus on optimizing encoding and alignment with the latitude and longitude grid; however, they often compromise the property of equal area. The rHEALPix DGGS (Gibb, 2016) offers a promising alternative for cadastral purposes, notably due to its equal-area cells and ellipsoidal approximation. Nonetheless, its maximum resolution, with an edge length of approximately 2 meters, and its geographic measure "adherence" pose challenges for application in cadastral mapping.

This deficiency extends to applications that integrate distributed ledger technologies (DLT), such as blockchains. The FOAM initiative, for example, employs a registry of Crypto-Spatial Coordinates (CSC) utilizing a geohash derived from H3 DGGS at resolution 15 (0.5 km cell edge) within a designated protocol (Benahmed Daho, 2020). This initiative, which emerged in the context of proof of location, provides a public, decentralized environment, employing tokens as incentives (Hobona & De Lathouwer, 2018). This underscores the necessity for a DGGS explicitly designed to meet the geodetic precision and area preservation demands essential for the legal certainty inherent in cadastral systems.

3 DESIGNING A PARALLELOGRAM DGGS

To develop a comprehensive global grid dedicated to terrestrial cadastral mapping, some essential criteria were meticulously evaluated to ensure the proposed grid model satisfies the precision, usability, and delimitation standards pertinent to geographic features and property records. Unlike the Goodchild criteria, which serve as indicators to compare and evaluate DGGS (Kimerling et al., 1999), the criteria employed for ITACaRT are for design and are outlined in Frame 1.

Frame 1 – Key design criteria for a DGGS customized for terrestrial cadastral mapping.

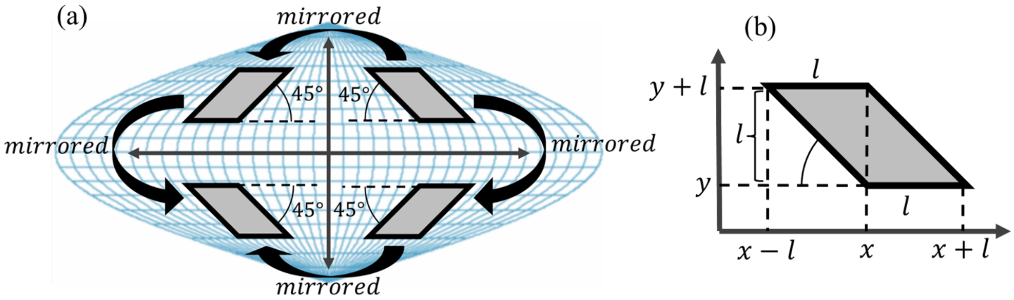
Criterion	Description
Purpose-Oriented	Prioritizes cadastral mapping requirements, with an emphasis on minimizing geometric distortions to ensure precise land measurements within the ellipsoidal framework.
Equal-Area Cells	Ensures uniform cell sizes for consistent quantification and valuation for technical and legal purposes.
GNSS Compatibility	Minimal cell size that guarantees high-precision positioning for integration with field data.
Simple Cell Shapes	Prefers quadrilaterals for computational simplicity and user familiarity.
Adequate Multi-Scale Views	Enables comprehensive and regional visualizations across multiple levels of detail.
Usability for Geoinformation Professionals	Aligns with Cartesian models commonly employed in surveying for intuitive manipulation by users.
Blockchain Integration	The indexing code must consider integration in transparent transactions and immutable records for cadastral operations.

Source: Authors (2025).

To fulfill the design criteria of usability and geodetic precision, the ITACaRT methodology uses base and height measurements obtained directly from the Earth's ellipsoidal model, which offers the most accurate Cartesian representation. This method, which maintains the base length and height of each cell, establishes an equal-area system and results in the sinusoidal cartographic projection on the ellipsoid (parallel planes projection). A significant benefit of this approach is that it produces a hierarchy of cells with areas consistent with the decimal system. This precise and intuitive quantification of area facilitates advanced applications, such as the straightforward tokenization of land parcels within blockchain systems, where a token can directly correspond to a standard metric area.

As previously discussed, related research employing square cells within this type of projection has resulted in significant angular distortion. To address this issue, the ITACaRT methodology employs parallelogram-shaped cells. This choice reflects the geometric characteristics of the sinusoidal projection on the Earth's model, which approximates a rhombus. The configuration of these parallelogram cells originating from the center of each globe quadrant creates a notable angle of approximately 45° (Figure 1). This angle varies across the ellipsoidal surface as the shape of the cells adapts to the Earth's curvature.

Figure 1 – DGGS cell's (a) quadrant and (b) parallelogram coordinates arrangement.



Source: Authors (2025).

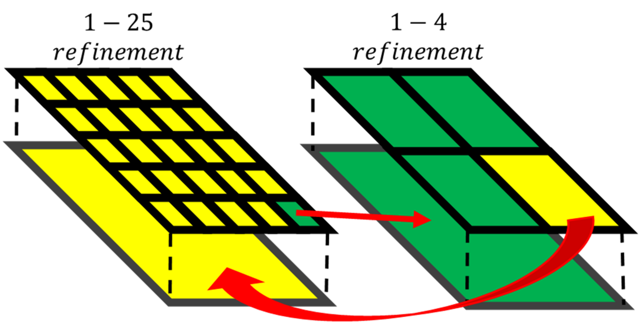
The particular geometry of each cell is characterized by the coordinates of its four vertices within the sinusoidal projection, as depicted in Figure 1. Let $\{x, y\}$ represent the coordinates of the lower-left vertex in the northeast quadrant, which functions as the cell's origin point. The length of the horizontal base of the parallelogram is denoted by l. In this specific geometric configuration, the vertical height of the parallelogram is also equal to l. Accordingly, the coordinates of the remaining vertices are defined as follows: $\{x + l, y\}$ for the lower-right; $\{x, y + l\}$ for the upper-right; and $\{x - l, y + l\}$ for the upper-left. The geometries of cells in the other quadrants are established by reflecting these coordinates across the x-axis for the southern quadrants and across the y-axis for the western quadrants.

3.1 A Compositional Hierarchical Indexing

A DGGS is characterized by its indexing method, which provides a unique identifier for every cell at all resolutions. Typically, an approach of linearizing the space is used with filling curves or assigning an atomic identifier based on a consistent hierarchical refinement. In contrast, ITACaRT introduces a compositional hierarchical index designed to represent cadastral features, particularly those originating from vector sources.

The foundation for this compositional index is a multi-scale grid hierarchy based on metric units, ensuring direct compatibility with real-world measurements and aligning with the decimal system. This alignment is achieved through a mixed refinement strategy designed to produce cells with intuitive, regular area values. To establish the hierarchy consistent with the decimal system, two refinement methods are implemented: a 1-to-4 subdivision in the level from 10 to 5 for each axis, analogous to a quaternary tree, and a 1-to-25 subdivision from 5 to 1 for each axis as well (see Figure 2).

Figure 2 – Hierarchical set of 1-to-25 and 1-to-4 refinement.



Source: Authors (2025).

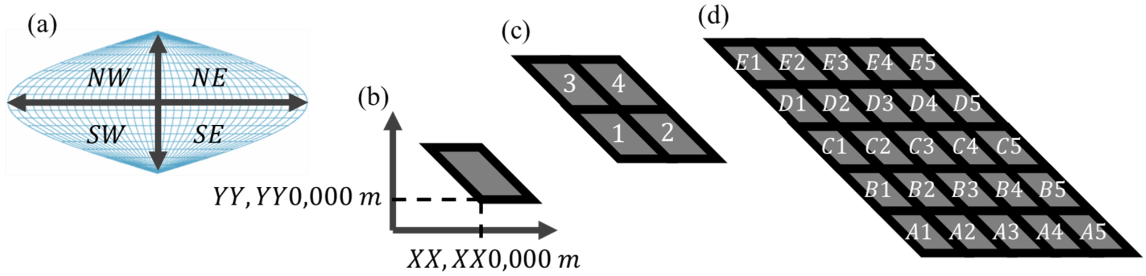
Considering that LAS necessitate a defined hierarchical framework for representing cadastral parcels across various scales, typically ranging from 1:500 for urban plots to 1:10,000 for larger rural regions (Williamson & Enemark, 1996). A requirement for the ITACaRT hierarchy is its capacity to effectively encompass this continuum, from expansive agricultural properties, which may extend several kilometers, to the centimeter-level accuracy mandated by modern Global Navigation Satellite System (GNSS) field surveys.

To meet these demands, ITACaRT delineates 14 resolution levels, commencing with a global quadrant, then progressing to a coarser cell size of 10 km and refining to a finest size of 1 cm. This multi-scale framework is realized through the previously described mixed refinement strategy. The subdivisions of 1-to-4 for even resolutions and 1-to-25 for odd resolutions establish a detailed sequence of cell sizes, appropriate for capturing both extensive land holdings and highly precise property boundaries, with a resolution commensurate with the accuracy of GNSS-based field data.

To facilitate the usability criterion, the ITACaRT index is designed to be human-readable and to reflect its hierarchical and compositional nature. The index string begins with a two-letter code identifying the global quadrant: Northeast (NE), Southeast (SE), Southwest (SW), or Northwest (NW).

Following the quadrant identifier, the coarsest resolution cells (10 km) are addressed by a pair of integer coordinates (X/Y) relative to the quadrant's origin. For instance, considering the WGS84 ellipsoid, the southeast quadrant contains approximately 2,003 cells along the equator and 1,000 cells along the central meridian. The combination of the quadrant code and these integer coordinates provides a globally unique address for each 10 km base cell. Subsequent finer resolutions are then encoded by appending refinement codes to this base address (Figure 3). The 1-to-4 refinements are indexed with the digits 1 through 4, while the 1-to-25 refinements use an alphanumeric grid from "A1" to "E5", resulting in a complete, compositional index string such as "SE(1400/0374(3(C2(3))))".

Figure 3 – Proposed DGGS indexing for (a) resolution 0, (b) resolution 1, (c) even resolutions, and (d) odd resolutions.



Source: Authors (2025).

Applying the DGGS indexing categorization (Mahdavi-Amiri et al., 2015), the ITACaRT compositional method is classified as a hierarchy-based approach. The complete index is constructed from four types of components, which correspond to different types of resolution, as detailed in Frame 2. This framework defines 14 resolution levels (0 to 13), ranging from global quadrants to cells with a base and height of 1 cm. The hierarchy alternates between two refinement rules: a subdivision from 1 to 4 is applied to generate even-numbered resolutions (2, 4, ..., 12), while a subdivision from 1 to 25 is applied to generate odd-numbered resolutions (3, 5, ..., 13).

Frame 2 – Proposed DGGS Resolutions descriptions.

Resolution	**Description**
Resolution 0 (Quadrants)	Primary global divisions.
Resolution 1 (Base cell)	Uniform 10km cells indexed using Cartesian coordinates in the sinusoidal projection.
Even Resolutions	Quaternary subdivisions (1-to-4) from parent cell.
Odd Resolutions	Subdivisions of 1-to-25 refinement indexing from parent cell.

Source: Authors (2025).

Through the utilization of this hierarchical indexing methodology, the DGGS framework guarantees the satisfaction of cadastral mapping requirements across various scales, ranging from extensive regional assessments to detailed parcel-level representations. Moreover, by employing the minimum visible line on cartographic representations as delineated in Jenny et al. (2008) and integrating Tobler (1987) sampling theory, the resolutions within DGGS can be correlated to particular dimensions and scales of visualization and analysis, as detailed in Table 1.

Table 1 – Proposed DGGS resolution sizes and corresponding cartographic scales.

Resolution	Base and height	Cell Area	Index	Visualization scale (Jenny et al., 2008)	Analysis scale (Tobler, 1987)
0	Quadrant	-	NE, NW, SE, SW	-	-
1	10 km	100 km^2	0000/0000 to 2003/1000	1:100,000,000	1:20,000,000
2	5 km	25 km^2	1 to 4	1:50,000,000	1:10,000,000
3	1 km	1 km^2	A1 to E5	1:10,000,000	1:2,000,000
4	500 m	250,000 m^2	1 to 4	1:5,000,000	1:1,000,000
5	100 m	10,000 m^2	A1 to E5	1:1,000,000	1:200,000
6	50 m	2,500 m^2	1 to 4	1:500,000	1:100,000
7	10 m	100 m^2	A1 to E5	1:100,000	1:20,000
8	5 m	25 m^2	1 to 4	1:50,000	1:10,000
9	1 m	1 m^2	A1 to E5	1:10,000	1:2,000
10	50 cm	2,500 cm^2	1 to 4	1:5,000	1:1,000
11	10 cm	100 cm^2	A1 to E5	1:1,000	1:200
12	5 cm	25 cm^2	1 to 4	1:500	1:100
13	1 cm	1 cm^2	A1 to E5	1:100	1:20

Source: Authors (2025).

A requirement of a DGGS, as formalized by the OGC (Gibb, 2021), is the capacity to support topological queries, including the determination of parent, child, and adjacent (neighbor) cells. A robust indexing scheme enables these relationships to be computed algorithmically from the cell identifiers themselves, without dependence on geometric coordinate calculations. This principle is exemplified in systems such as the DE-9IM computed cell IDs of rHEALPix (Gibb, 2016). The ITACaRT index is explicitly engineered to facilitate such operations through its transparent hierarchical structure.

Parent and child relationships within ITACaRT are inherently embedded in the index string. A parent cell is identified by removing the terminal component of its index. Conversely, the children of a cell are produced by appending all permissible refinement codes for the subsequent resolution level. Determining neighboring cells at the same resolution varies depending on the specific type of resolution, as outlined below for northeast quadrant, considering the mirroring of quadrants, which implies that ITACaRT does not utilize negative indexes.

a) Resolutions 0 and 1: The neighborhood is delineated using integer arithmetic based on the 10 km (XXXX/YYYY) coordinates. Specifically, for the upper cell, the Y-coordinate index diminishes by 1; for the lower cell, it increases by 1. Similarly, for the left and right cells, the X index decreases and increases by 1, respectively. The boundaries of the quadrants adhere to a straightforward deflection rule of the neighboring index when the index X or Y is zero or situated at a meridian boundary.

b) Even resolutions: For neighboring cells within the same parent cell, the approach adheres to a 2x2 quad-tree pattern. Assuming child cells are numbered 1-4, vertical adjacency (north/south) is determined by adding or subtracting 2 to the index, while horizontal adjacency (east/west) is established by adding or subtracting 1. The procedure for identifying a neighboring cell located in a different parent cell involves an iterative process, comprising the following steps: ascend one level to the parent, identify the parent's neighbor, and then descend to the corresponding child cell.

c) Odd resolutions: For neighbors within the same parent cell (a 5x5 grid), adjacency is also determined algorithmically. Horizontal neighbors are identified by incrementing or decrementing the numeric component of the index (e.g., from C2 to C3), with a wrap-around logic connecting columns 5 and 1. Vertical neighbors are identified by incrementing or decrementing the alphabetic component of the index (e.g., from C2 to B2), with a similar wrap-around connecting rows E and A.

The ITACaRT indexing method employs a distinctive syntax to facilitate its compositional nature. The index utilizes parentheses "()" to indicate a descent through hierarchical levels and a comma "," to separate multiple sibling cells at an identical resolution level. This structure permits a single index string to represent not only a solitary, terminal cell but also a complex region comprising multiple cells. Such an approach marks a fundamental departure from the atomic identifiers employed in numerous other DGGS.

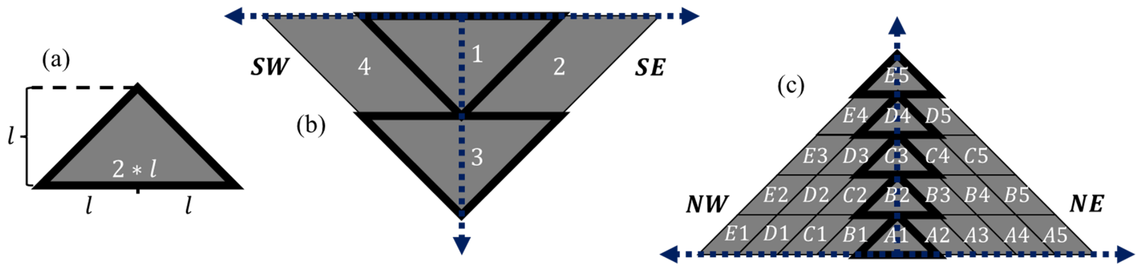
This compositional structure is particularly advantageous for representing vector features. For instance, a land parcel at resolution 13 encompassing two adjacent cells, C1 and C2, which are children of cell 4 at resolution 12, could be denoted by a single index: "...4(C1,C2)". While traditional DGGS would record this as an unstructured list of two discrete atomic identifiers, the ITACaRT compositional index maintains the hierarchical relationship and sibling connection within a unified, descriptive identifier. Regarding graph-based data models, recognized for their enhanced efficiency and topologically-aware storage and analysis (Kan et al., 2017), this tree-like configuration is intrinsically well-suited for implementation.

3.2 DGGS behavior

Applying the same parallelogram geometry to a quadrant of the globe results in discontinuities along the boundaries of the quadrant's meridian. We propose a solution for the prime meridian and an alternative for the 180° meridian.

To ensure the equal area distribution of the DGGS cell between the eastern and western quadrants, we propose an alternative cell geometry that encompasses the prime meridian. A triangle has been chosen for its analogous properties to a parallelogram regarding base and height, wherein the cell index intersects with the prime meridian and functions as the midpoint of the base of an isosceles triangle, with the base being twice the height. This configuration ensures that the cell is mirrored relative to the meridian (Figure 4). In this context, the corresponding upper point of the standard DGGS parallelogram within this triangle will be the lower left point. This methodology applies to the grid system at a resolution of 1 (10x10 km) and its lower resolutions, implying that for finer resolutions (2 to 13), the indexing logic does not create separate western cells along this boundary; instead, they are considered part of the hierarchical subdivision of the adjacent eastern cells. Furthermore, cells in resolution 1 with the X index equal to 0 in the western quadrants will be non-existent.

Figure 4 – The (a) grid triangle and the prime meridian grid behavior for (b) 1-to-4 refinement for the southern hemisphere and (c) 1-to-25 refinement for the northern hemisphere.

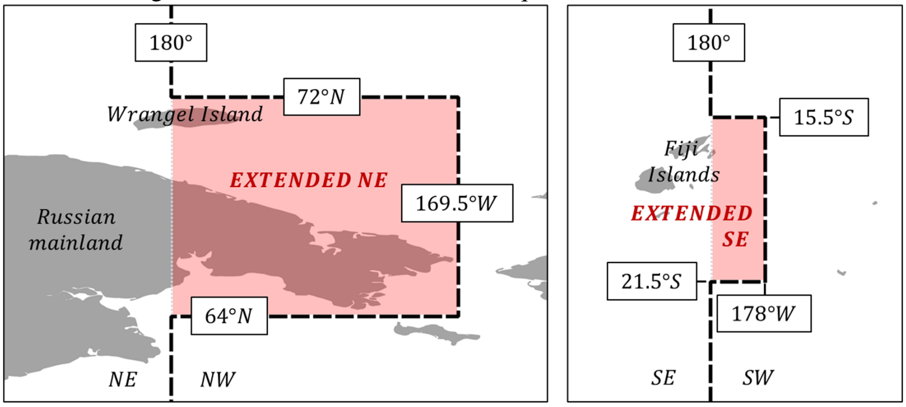


Source: Authors (2025).

Regarding the antemeridian boundary at 180° longitude, it is impractical to maintain uniform cell areas universally. Consequently, to address the terrestrial cadastral mapping requirements, we intend to adjust the grid at the landmasses intersected by the 180th meridian: the Fiji Islands, a segment of the Russian mainland in Chukotka Autonomous Okrug, and Wrangel Island. The landmass in Antarctica along this meridian has been excluded due to its limited cadastral applications. As a result, some DGGS cells located in the oceans and Antarctica will have unequal area sizes.

Therefore, we expanded two areas of the eastern quadrants to include lands crossing the antemeridian: the Fiji Islands, extended to the 178° west longitude between the latitudes of 15.5° and 21.5° south, and the Russian intersection, which covers the mainland, Wrangel Island, and some nearby islands, extended to the 169.5° west longitude between the latitudes of 64° and 72° north (Figure 5). We adopted a precision of 0.5°, which is the highest and easiest-to-use longitude that does not cross any land except Antarctica.

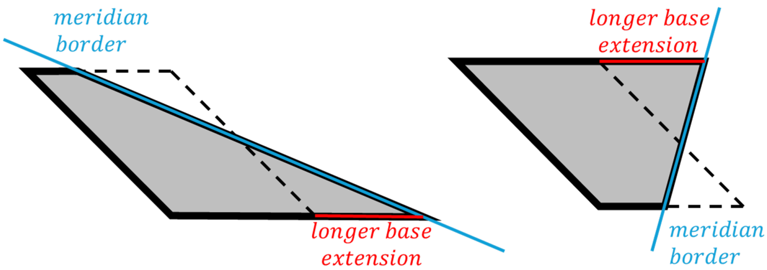
Figure 5 – The limits of the eastern quadrants extension areas.



Source: Authors (2025).

In light of the above, we suggest utilizing a trapezoidal shape for cells that do not conform to the standard of equal area—specifically, those intersecting with the antemeridian or the meridian boundary of an extension area—subject to the following condition: if a vertex of the parallelogram on the side opposite the prime meridian exceeds the boundary, then that side shall be constrained within the boundary line, thereby extending the longer base of the trapezoid (see Figure 6). This rule is applied solely to the cells within this specified condition and not to all subsequent resolutions.

Figure 6 – The DGGS trapezoidal cells examples.



Source: Authors (2025).

Aiming for equality of the DGGS cell areas and maintaining equidistance along the x and y axes, similar to the sinusoidal projection, involves that the shape of the cells undergoes modification around the terrestrial ellipsoid. This suggests that although the parallelogram retains its fundamental form, the lengths of its eastern and western sides, as well as the base angles, may vary, while preserving equal areas for all cells, with the exception of the antemeridian. Consequently, this results in angular deformations, which will be addressed in the subsequent section.

4 DISCUSSIONS

To evaluate the proposed DGGS design, each development decision is mapped back to the initial criteria established for cadastral applications. Frame 3 provides a systematic summary of how the ITACaRT design fulfills each of these criteria. By adhering to a Cartesian-like framework to ensure usability, the proposed DGGS accommodates the hierarchical needs of cadastral mapping across various scales while preserving rigorous cartographic consistency. This approach establishes a robust foundation for both precise property delineation and advanced applications, such as distributed ledger technologies like blockchain.

Frame 3 – Applied solutions for the design criteria in the DGGS design.

Criteria	Applied solution
Purpose-Oriented	The DGGS design is intricately aligned with the particular requirements of cadastral mapping, underscoring the synchronization of grid resolutions with standard cadastral map scales (ranging from 1:500 to 1:10,000). The focus on reducing geometric distortions by approximating the cell to the rhombic globe representation of the sinusoidal projection on the ellipsoidal model ensures precise land quantification and delineation.
Equal-Area Cells	The DGGS centrally employs uniform grid cells referenced by the principles of the sinusoidal projection, ensuring consistency in quantification and valuation. The equal-area property is maintained across the entire globe, with specific, controlled exceptions at the 180° meridian boundary.
GNSS Compatibility	The system integrates seamlessly with GNSS technology by being based on the WGS84 ellipsoid and providing resolutions down to the centimeter-level, matching the precision of modern field survey data.
Simple Cells Shape	Although square cells are common, parallelograms are favored due to their enhanced capacity to manage angular distortion, which is inherent in the sinusoidal projection, ensuring greater geometric fidelity globally.
Adequate Multi-Scale Views	The hierarchical subdivision method, encompassing 1-to-4 and 1-to-25 refinements, facilitates a granular and consistent sequence of cell sizes across 14 resolutions, from global quadrants down to centimeter-level.
Usability for Geoinformation Professionals	The Cartesian-like approach of the grid and its indexing facilitates intuitive manipulation and aligns with the conventional workflows of surveyors and other geoinformation professionals.
Blockchain Integration	The hierarchy, based on the decimal system, results in cells with intuitive metric areas (e.g., 1 km², 100 m²), which directly facilitates the tokenization of land parcels in blockchain applications where a token can represent a standard unit of area.

Source: Authors (2025).

Beyond the internal design criteria, a critical aspect of a modern DGGS is its adherence to international standards, which ensures interoperability and formal rigor. The primary standard in this domain is the OGC Abstract Specification Topic 21, which underpins the ISO 19170 series (Gibb, 2021). This specification outlines two main conformance classes relevant to ITACaRT: the foundational DGGS Core and the more specific Equal-Area Earth Reference System (EAERS). Frame 4 and Frame 5 present a detailed, requirement-by-requirement analysis of ITACaRT's compliance with both classes.

Frame 4 – OGC DGGS Core Requirements analysis for ITACaRT.

ID	Requirement (Simplified)	ITACaRT Compliance	Justification / Comments
6	Harmonized Model	Met	The implementation of the ITACaRT architecture can be referenced through the data model depicted in Figure 13 of Gibb (2021).
7	Defined CRS	Met	ITACaRT utilizes the WGS84 datum to guarantee compatibility with GNSS.
8 to 10	Global, Complete and Unique Domain	Met	The system comprehensively encompasses the WGS84 ellipsoid through a specialized approach for bordering meridians.
11	Simple Cell Geometry	Met	Cells are parallelograms, which are simple polygons that do not intersect with themselves.
12	Direct Position	Met	Each cell possesses a designated representative position (the lower-left vertex), which resides within the boundary of the cell.
13	Unique Address	Met	The compositional hierarchical index guarantees a globally unique compositional identifier for each cell.
14, 15	Hierarchical Grid Sequence	Met	The system is structured in 14 ordered resolution levels.
16	Quantization Functions	Met	The compositional index is designed to associate vector data with sets of cells and can be referenced by Figure 14 of Gibb (2021).
17	Topological Query Functions	Met	The index structure allows for the algorithmic determination of parent, child, and neighbor relationships and can be referenced by Figure 16 of Gibb (2021).
18, 19	Interoperability Functions	Met (by design)	The system is designed to allow data export to standard geospatial formats.

Source: Authors (2025), based on Gibb (2021).

Frame 5 – OGC Equal-Area Earth Reference System (EAERS) Requirements analysis for ITACaRT.

ID	Requirement (Simplified)	ITACaRT Compliance	Justification / Comments
20	EAERS Harmonized Model	Partially Met	The implementation of the ITACaRT architecture can be referenced by the data models in Figures 20 and 22 of Gibb (2021). However, for Figure 21, due to the system's Direct Surface Tessellation, the polyhedral interface cannot be achieved.
21	Equal Area (cellEqualSized) Constraint	Partially Met	Even with the reference to the properties of the sinusoidal projection, which is equal in size, the trapezoidal cells at the antemeridian do not possess equal dimensions. Nonetheless, for land cadastre purposes, this can be deemed acceptable.
22 to 25	Initial Tessellation from Polyhedron	Not Met	ITACaRT employs a Direct Surface Tessellation grounded in a projection methodology to emphasize absolute geodetic accuracy on the ellipsoid, thereby circumventing the intermediary abstraction layer of a polyhedron.
26	Cells as Simple 2D Polygons	Met	The cells are parallelograms, except at bordering meridians, where cells may be triangles or trapezoids.
27	Representative Position at Centroid	Partially Met	In order to prioritize the "Usability" criterion and maintain a Cartesian-like feel, the representative position is designated as a vertex rather than the centroid. However, further implementation may represent the cell's centroid.
28, 29	Equal Area (within error budget)	Partially Met	The sinusoidal projection is entirely equal-area; therefore, the system satisfies this criterion with no error budget concerning area, excepting for the trapezoidal cells.

Source: Authors (2025), based on Gibb (2021).

The analysis presented in the tables demonstrates that ITACaRT fully adheres to the foundational requirements of the DGGS Core, establishing it as a robust and valid DGGS. Regarding the more specific EAERS class, the system shows partial compliance. These points of divergence, however, are not shortcomings but rather deliberate design trade-offs made to fulfill the system's primary purpose. The choice of a Direct Surface Tessellation over a projected polyhedron, and the pragmatic handling of the antemeridian boundary with non-equal-area cells, prioritize the practical needs of a cadastral system—such as absolute geodetic fidelity and applicability to inhabited landmasses—over the theoretical purity of a universally uniform grid.

The representation of vector features within a DGGS can be achieved via two primary approaches: cell filling (tessellation) and vertex representation. The cell filling method depicts a polygon through the comprehensive set of cells it encompasses. Its principal advantage lies in the capacity to determine the feature's area by a straightforward count of the cells, thereby eliminating projection distortions. Nevertheless, this technique may become exceedingly verbose and demanding in storage at higher resolutions. Conversely, the vertex representation method retains solely the identifiers of the cells corresponding to the polygon's vertices, analogous to conventional vector data, wherein polygonal features can be stored similarly by utilizing cells as vertices within an algorithmic framework (Tong et al., 2013). This approach is markedly more compact, thereby offering significant efficiency in storage.

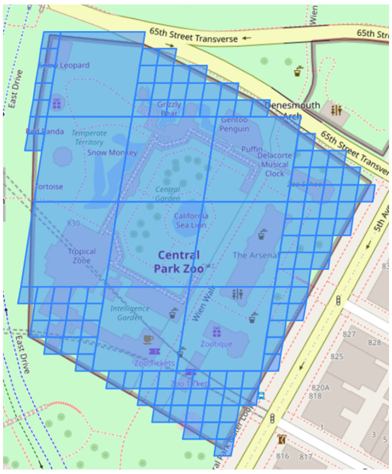
Figure 7 and the accompanying code examples demonstrate these two methodologies utilizing the ITACaRT index to depict the same polygon. The verbosity inherent in the initial example, which employs a compositional fill, explicitly illustrates the storage costs associated with that method, even at a relatively coarse resolution of 10x10m (Resolution 7). Conversely, the second example, which utilizes cell IDs as vertices, is markedly more succinct.

a) Compositional Fill Representation (Resolutions 6 and 7): NW(0625/0451(1(E1(3(B2(4(A2,B2,B3,B4, C2,C3,C4,C5,D1,D2,D3,D4,D5,E1,E2,E3,E4,E5)),B3(3(C1,D1,D2,E1,E2,E3,E4)),C2(1(A5,B5, C5, D4,D5,E4,E5),2,3(A4,A5,B3,B4,B5,C3,C4,C5,D2,D3,D4,D5,E2,E3,E4,E5),4),C3(1,2(A1,B1, B2, B3, C1,C2,C3,C4,D1,D2,D3,D4,E1,E2,E3,E4,E5),3,4),D2(1(A1,A2,A3,A4,A5,B2,B3,B4,B5, C3, C4, C5, D5),2,4(A3,A4,A5,B5)),D3(1,2,3(A1,A2,A3,A4,A5,B1,B2,B3,B4,B5,C2,C3,C4,C5,D4,D5), 4), D4(1 (D1,E1),3(A1,B1,C1,D1,E1))))))).

b) Vertex Representation (Resolution 13): NW(0625/0451(1(E1(3(C3(2(C5(1(A2(3(C3(3(C4)))))))),

B2(4(A2(1(D5(4(A3(1(D4)))))))), D2(1(B1(1(B2(4(C2(4(E5))))))), 4(B3(2(A4(4(B4(2(D5)))))))), D3(3(E5(2(D5(1(D5(2(E3)))))))), D4(3(E1(4(D2(3(C3(4(B1))))))), 1(E1(2(D2(4(C5(1(B1))))))))
))))).

Figure 7 ─ An example of the ITACaRT cells at resolutions 6 and 7 within an OpenStreetMap (OSM) base.

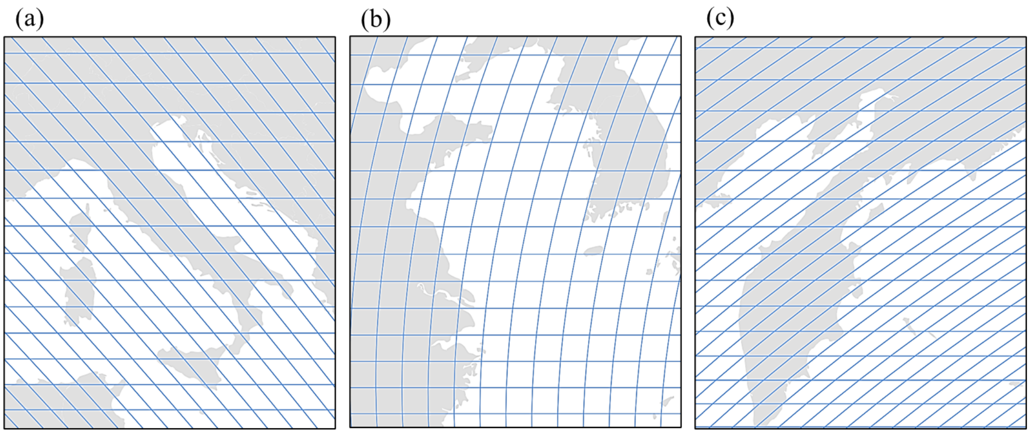


Source: Authors (2025).

A qualitative analysis suggests that, for storage efficiency, the vertex representation is preferable. Although this method may still seem verbose compared to traditional latitude and longitude coordinates, a straightforward comparison is difficult. An accurate assessment is therefore complex, requiring consideration of binary encoding for blockchain contexts and performance across different storage models. Ultimately, any comparison must weigh the verbosity of the index against the overarching systemic advantages of a unified, hierarchical reference system.

A core trade-off inherent in the ITACaRT design, arising from the "design trilemma", involves the acceptance of angular distortion in order to achieve perfect area preservation. A qualitative analysis of this distortion is conducted to examine how the shape of the parallelogram cells varies across the entire surface of the flat sinusoidal projection plane, with all cells initially characterized as identical parallelograms featuring a 45° acute angle. Nevertheless, when these cells are projected onto the WGS84 ellipsoid, this uniform shape undergoes predictable distortion, as exemplified in the illustrations provided in Figure 8.

Figure 8 ─ Parallelogram grid angular distortion at same quadrant observed (a) in proximity to the prime meridian within the Italian Peninsula, (b) at mid-latitudes and mid-longitudes in the East China Sea, and (c) at high latitudes and longitudes in the Kamchatka Peninsula.



Source: Authors (2025).

In regions near the equidistant lines of the sinusoidal projection, such as the 0° latitude or longitude lines—which include areas like the Italian Peninsula—the distortion remains minimal. The cells on the ellipsoid closely preserve the 45° parallelogram shape as observed on the projection. As the grid extends toward mid-latitudes and longitudes (for example, around 45° latitude and 90° longitude), the shearing effect diminishes.

In the East China Sea, the parallelograms become more orthogonal and resemble squares. This indicates a zone of preferential angular distortion, where the shape deviates significantly from the 45° design baseline but transforms into a more familiar orthogonal grid. Conversely, the most pronounced shearing distortion occurs at high latitudes and longitudes, distant from the origin. In the Kamchatka Peninsula, the acute 45° angle of the projected parallelogram transforms into a severely obtuse angle exceeding 135°. This qualitative analysis demonstrates that ITACaRT's angular distortion is systematic and predictable, following inherent patterns of the sinusoidal projection, and most notably, it preserves the simple parallelogram topology globally, fulfilling a key design criterion despite the variation in geometrical angles.

The hierarchical compositional index of ITACaRT bears significant implications for data storage and analysis, indicating a shift from conventional relational models. Relational databases often exhibit inefficiency when navigating deeply hierarchical or networked data, as topological queries necessitate multiple, computationally intensive join operations that compromise performance with increasing dataset complexity. Conversely, graph databases are explicitly designed to accommodate and traverse intricate relationships, rendering them inherently suitable for managing topologically-aware network data. Although Kan et al. (2017) concentrated on power grid networks, their findings are directly pertinent: the tree-like architecture of the ITACaRT index, which inherently encodes parent-child and sibling relationships, can be seamlessly mapped onto a graph model wherein each cell functions as a node and topological connections are represented as persistent edges. This methodology not only enhances query efficiency for complex vector features encapsulated by the compositional index but also offers a robust framework for examining the intersection of vector-derived and raster-derived data within a unified DGGS.

The distinctive characteristics of ITACaRT — specifically its explicit area control, Cartesian-like methodology, and hierarchical encoding — establish it as a formidable instrument for the integration of cadastral information into broader geospatial infrastructures. As a multi-tiered, global framework, it can serve as a technological foundation for SDI and LAS, enabling the aggregation of complex land information. Moreover, its design for blockchain integration has the potential to enhance the geospatial components of a LAS by ensuring transparency and immutable records. Beyond these primary cadastral functions, the framework's capabilities extend to other geospatial tasks. An innovative approach involves employing DGGS as a backend analytical model for conventional GIS operations (Hojati et al., 2022). This indicates that ITACaRT could function as a foundational analytical structure, managing discrete data and elucidating associated uncertainties, while maintaining the user-friendly interface characteristic of GIS, a feature facilitated by its intuitive Cartesian methodology.

5 CONCLUSIONS AND FUTURE WORK

This paper addresses a significant gap in the literature by introducing ITACaRT, a Discrete Global Grid System specifically tailored for the stringent requirements of terrestrial cadastral mapping. While existing DGGS primarily emphasize other parameters, such as web-scale logistics or computational efficiency, ITACaRT was developed to establish a robust foundation for contemporary Land Administration Systems by integrating geodetic precision with the legal and operational stipulations of land tenure. The comprehensive conceptual methodology has been elaborated, based on an equal-area, direct-on-ellipsoid tessellation utilizing parallelogram cells to manage the predictable angular distortion inherent in its underlying projection.

A significant contribution of this research is the development of a Compositional Hierarchical Indexing method. Unlike the atomic identifiers commonly used in other DGGS, this structure is explicitly engineered to represent complex vector features more effectively, a vital attribute for cadastral parcels. Moreover, the analysis of ITACaRT's characteristics in relation to the OGC DGGS Core standards and the Equal-Area Earth Reference System standards verifies its validity as a formal DGGS, with its intentional deviations from complete compliance reflecting strategic design decisions aimed at enhancing cadastral usability. Through the establishment of this comprehensive conceptual framework, ITACaRT is positioned as a feasible spatial infrastructure for the integration of advanced technologies such as blockchain, thereby bridging the gap between traditional cartography and digital land administration.

The conceptual validation of ITACaRT elucidates a comprehensive agenda for forthcoming research, which may be organized into three principal domains: implementation, quantitative evaluation, and practical application.

Initially, the foremost priority is the development of a reference software implementation. This encompasses the creation of algorithms and data structures, likely modeled on a tree-like structure as initially suggested, to facilitate coordinate transformations, indexing, and topological queries. An aspect of this phase will be to prototype the system utilizing graph database technologies to empirically validate the hypothesis that this model provides superior performance in managing and querying the compositional index. This endeavor will also include the development of a binary codification of the index to enhance storage and retrieval efficiency, a critical step for its anticipated integration with blockchain systems.

Secondly, a comprehensive quantitative quality assessment is necessary to advance beyond the conceptual and qualitative analyses presented herein. This entails a rigorous statistical examination of angular and area distortion across all grid resolutions and geographic regions. A comparative performance benchmark against established DGGS, such as H3, S2, and rHEALPix, must be performed, emphasizing metrics pertinent to cadastral operations, including storage efficiency for complex polygons and query speed for adjacency and containment.

Ultimately, the definitive validation of ITACaRT will be achieved through its application in real-world contexts. This involves implementing pilot projects with diverse and complex cadastral datasets from urban and rural settings to assess its operational workflows. Additionally, these initiatives can refine the framework and thoroughly explore its potential as a backend analytical model for traditional GIS (Hojati et al., 2022), as well as the foundational spatial layer for secure, transparent, and immutable blockchain-based land registries.

Acknowledgments

This work has been supported by the Brazilian Federal Agency for Support and Evaluation of Graduate Education (CAPES) – Finance Code 001. Elcio Hideiti Shiguemori is partially funded by the National Research Council of Brazil (CNPq) (316948/2023-3).

Authors' Contributions

This article was prepared based on the contributions of all authors. I.N.S.: Conceptualization, Methodology, Writing – original draft; G.D.: Writing – review & editing; E.H.S.: Writing – review & editing, Supervision.

Conflict of Interest

The authors declare no conflict of interest.

References

Benahmed Daho, A. (2020). CRYPTO-SPATIAL: An open standards smart contracts library for building geospatially enabled decentralized applications on the Ethereum blockchain. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLIII-B4-2020*, 421–426. https://doi.org/10.5194/isprs-archives-xliii-b4-2020-421-2020

Bondaruk, B., Roberts, S. A., & Robertson, C. (2020). Assessing the state of the art in Discrete Global Grid Systems: OGC criteria and present functionality. *Geomatica*, *74*(1), 9–30. https://doi.org/10.1139/geomat-2019-0015

Cheng, C., Tong, X., Chen, B., & Zhai, W. (2016). A subdivision method to unify the existing latitude and longitude grids. *ISPRS International Journal of Geo-Information*, *5*(9), 161. https://doi.org/10.3390/ijgi5090161

Cooper, A. K., van Huyssteen, E., Das, S., Coetzee, M., & Mans, G. (2014). Assessment of spatial data infrastructures. *Town and Regional Planning*, *64*, 65–75.

Dawidowicz, A., & Źróbek, R. (2017). Land administration system for sustainable development: Case study of Poland. *Real Estate Management and Valuation*, *25*(1), 112–122. https://doi.org/10.1515/remav-2017-0008

Gibb, R. (2016). The rHEALPix Discrete Global Grid System. *IOP Conference Series: Earth and Environmental Science*, *34*, 012012. https://doi.org/10.1088/1755-1315/34/1/012012

Gibb, R. (2021). *Topic 21 - Discrete Global Grid Systems - Part 1 Core Reference system and Operations and Equal Area Earth Reference System* (OGC Discussion Paper No. 20-040r3). Open Geospatial Consortium. https://doi.org/10.62973/20-040r3

Goodchild, M. F. (2018). Reimagining the history of GIS. *Annals of GIS*, *24*(1), 1–8. https://doi.org/10.1080/19475683.2018.1424737

Goodchild, M. F., Guo, H., Annoni, A., Bian, L., Bie, K., Campbell, F., Craglia, M., Ehlers, M., van Genderen, J., Jackson, D., Lewis, A., Pesaresi, M., Remetey-Fülöpp, G., Simpson, R., Skidmore, A., Wang, C., & Woodgate, P. (2012). Next-generation Digital Earth. *Proceedings of the National Academy of Sciences of the United States of America*, *109*, 11088–11094. https://doi.org/10.1073/pnas.1202383109

Hobona, G., & De Lathouwer, B. (2018). *Geospatial standardization of Distributed Ledger Technologies* (OGC Discussion Paper No. OGC 18-041r1). Open Geospatial Consortium. http://www.opengis.net/doc/DP/dlt-blockchain-review

Hojati, M., Robertson, C., Roberts, S., & Chaudhuri, C. (2022). GIScience research challenges for realizing discrete global grid systems as a Digital Earth. *Big Earth Data*, *6*(3), 358–379. https://doi.org/10.1080/20964471.2021.2012912

Jenny, B., Jenny, H., & Räber, S. (2008). Map design for the Internet. In W. Cartwright, G. Gartner, L. Meng, & M. P. Peterson (Eds.), *International perspectives on maps and the Internet* (pp. 31–48). Springer. https://doi.org/10.1007/978-3-540-72029-4_3

Kan, B., Zhu, W., Liu, G., Chen, X., Shi, D., & Yu, W. (2017). Topology modeling and analysis of a power grid network using a graph database. *International Journal of Computational Intelligence Systems*, *10*(1), 1355–1363. https://doi.org/10.2991/ijcis.10.1.96

Kimerling, A. J., Sahr, K., White, D., & Song, L. (1999). Comparing geometrical properties of global grids. *Cartography and Geographic Information Science*, *26*(4), 271–288. https://doi.org/10.1559/152304099782294186

Li, M., & Stefanakis, E. (2020). Geospatial operations of Discrete Global Grid Systems—a comparison with traditional GIS. *Journal of Geovisualization and Spatial Analysis*, *4*(2). https://doi.org/10.1007/s41651-020-00066-3

Ma, T., Zhou, C., Xie, Y., Qin, B., & Ou, Y. (2009). A discrete square global grid system based on the parallels plane projection. *International Journal of Geographical Information Science*, *23*(10), 1297–1313. https://doi.org/10.1080/13658810802344150

Mahdavi-Amiri, A., Alderson, T., & Samavati, F. (2015). A survey of Digital Earth. *Computers & Graphics*, *53*, 95–117. https://doi.org/10.1016/j.cag.2015.08.005

Peterson, P. R., Percivall, G., Purss, M. B. J., Samavati, F., & Gibb, R. (2015). Discrete Global Grid Systems - A Framework for the next Era in Big Earth Data. *AGU Fall Meeting Abstracts*, *2015*, IN43B–1729.

Rajabifard, A. (Ed.). (2019). *Sustainable Development Goals connectivity dilemma: Land and geospatial information for urban and rural resilience*. CRC Press. https://doi.org/10.1201/9780429290626

Sahr, K., White, D., & Kimerling, A. J. (2003). Geodesic Discrete Global Grid Systems. *Cartography and Geographic Information Science*, *30*(2), 121–134. https://doi.org/10.1559/152304003100011090

Silva, I. N., Shiguemori, E. H., & Dietzsch, G. (2025). Designing a parallelogram Discrete Global Grid System for terrestrial cadastral mapping. *Proceedings of the Brazilian Symposium on GeoInformatics*.

Snyder, J. P. (1987). *Map Projections: A working manual*. United States Government Printing Office.

Tobler, W. (1987). Measuring spatial resolution. *Proceedings, Land Resources Information Systems Conference*, *1*, 12–16.

Tong, X. C., Ben, J., Liu, Y. Y., & Zhang, Y. S. (2013). Modeling and expression of vector data in the hexagonal Discrete Global Grid System. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XL-4/W2*, 15–25. https://doi.org/10.5194/isprsarchives-XL-4-W2-15-2013

White, D., Kimerling, A. J., Sahr, K., & Song, L. (1998). Comparing area and shape distortion on polyhedral-based recursive partitions of the sphere. *International Journal of Geographical Information Science*, *12*(8), 805–827. https://doi.org/10.1080/136588198241518

Williamson, I. P., & Enemark, S. (1996). Understanding cadastral maps. *Australian Surveyor*, *41*(1), 38–52. https://doi.org/10.1080/00050336.1996.10558593

Williamson, I. P., Enemark, S., Wallace, J., & Rajabifard, A. (Eds.). (2010). *Land administration for sustainable development*. Esri Press.

Yomralioglu, T., & McLaughlin, J. (Eds.). (2017). *Cadastre: Geo-information innovations in land administration*. Springer. https://doi.org/10.1007/978-3-319-51216-7

Zhou, C., Ma, T., Yang, L., & Qin, B. (2007). Parallels plane projection and its geometric features. *Science in China Series D: Earth Sciences*, *50*(S1), 176–180. https://doi.org/10.1007/s11430-007-5011-8

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