

A Study on Novel Grid-based Spatiotemporal Information Management Techniques

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Abstract

To address the problems and challenges of spatiotemporal information management in the era of big data, this study utilizes the Earth-based spatiotemporal grid framework technology. It establishes a spatial management model based on spatiotemporal grids and proposes a timeline-based "scene-grid-entity" dynamic coordinated management approach for spatial data. This method realizes grid-based construction of spatial scenes, grid-based definition of spatial entities, and grid-based management mechanisms for spatial activities. A novel spatiotemporal information organizational management model and storage structure are designed, enabling the fusion of multi-source heterogeneous spatial data, unified organizational management of spatiotemporal big data, and multi-scale representation. The proposed framework demonstrates significant application value in fields such as national territorial spatial planning and smart city management.

1. Introduction

The era of big data has generated a vast amount of spatiotemporal data, such as facility entity data, transportation trajectory data, and environmental field data. Spatial information is abstracted and described from geospatial entities, representing their spatial and attribute characteristics semantically (Li et al., 2004). It is characterized by multi-source acquisition methods, heterogeneous storage formats, multi-temporal and multi-scale properties, multi-semantic interpretations, and distributed features. The temporal dimension further adds variability to spatial information (entities) (Wang et al., 2017).

The multi-source nature and variability of spatiotemporal information make unified organizational management challenging, particularly in establishing associations between entities and diverse data sources. Existing coordinate-time sequence transformation methods for spatiotemporal data fail to fundamentally resolve these issues, necessitating the development of a novel spatiotemporal data model.

The Earth-based spatiotemporal grid aligns with the computational demand for discrete spatiotemporal information processing. It overcomes the nonlinear geometric constraints of traditional map coordinates, providing a new approach for the unified management of massive, multi-source, multi-scale, and dynamic spatiotemporal information (Li et al., 2004; Luo et al., 2023).

2. Challenges in Spatiotemporal Information

With the rapid development of science and technology, especially the advancement of modern data acquisition technologies such as sensor networks and mobile terminals, spatial information data from multiple sources and domains has experienced exponential growth (Liu et al., 2021). The scope of geospatial information has expanded from the Earth's surface to underground, underwater, aerial, and even outer space environments. A critical challenge now is how to accurately describe the locations and coverage ranges of spatial entities across maritime, land, air, and space domains, enable

standardized identification of regional positions, and achieve unified organizational management of massive data across these heterogeneous spaces.

Spatiotemporal information exhibits explosive growth, with increasing data volume, diversity, and dimensionality. It presents characteristics such as large information granularity differences, extensive spatiotemporal spans, isolation, fragmentation, weak associations, and even contradictions. These data require comprehensive evaluation and integration into higher-resolution, up-to-date spatial data. Such data must then be converted into spatiotemporal big data under a unified mathematical framework for organizational management, enabling standardized data and capabilities delivery to serve military and societal applications, thereby unlocking the immense value of spatial information (Liang et al., 2023; Zhao et al., 2023).

Current GIS, BIM, remote sensing imagery, and various spatial attribute data face significant challenges due to their differing organizational structures. These datasets often vary in data formats and coordinate systems, lacking a unified framework for spatial integration. This heterogeneity makes multi-source spatiotemporal data management highly complex. Furthermore, under large-scale spatial activity scenarios, existing spatial information platforms exhibit weak organizational expression capabilities and nearly non-existent decision-supporting functions, particularly lacking spatiotemporal dynamic collaborative support capabilities. There is an urgent need to adopt an Earth-based spatial grid framework to achieve unified organizational management and comprehensive utilization of spatiotemporal information.

3. Current Status of Spatiotemporal Grid Development

Traditional geographic information systems (GIS) are built on Euclidean, Cartesian, and positivist concepts for understanding geographic space and environments. Their core principle is to partition the geographic world into well-defined, continuous, non-overlapping polygonal spatial units. Complex geographic spaces are simplified into strictly classified, simple geometric configurations (points, lines, surfaces, polygons, networks, bounded regions, etc.). Traditional grid modeling of

geographical environments relies primarily on map projections to establish planar grids for the organization of environmental data (Wang et al., 2005; Zhou et al., 2009; Chen et al., 2011). However, accurately describing the spatial locations and analyzing diverse activities across maritime, land, air, and space domains now requires a new theoretical framework distinct from traditional GIS. The directly relevant methodology is spatial grid partitioning.

The Earth spatial reference grid divides the Earth's space into shape-consistent, regularly sized multi-level grids. It aligns with existing Earth surface grid systems and comprehensively represents spatial data across air, space, terrestrial, and underground domains, forming a theoretical foundation for Earth spatial information expression.

Early examples include the Ballard grid and Cube-sphere grid, initially proposed for seismic wave analysis. The Global Area Reference System (GARS) grid, introduced by the U.S. National Geospatial-Intelligence Agency (NGA) in 2006, serves as a standardized reference system for the U.S. Department of Defense. It is primarily used to meet the needs of coordinated operations between combat systems and command structures in joint operations, enabling rapid geographic area localization for battlefield coordination, operational synchronization, and large-scale search-and-rescue missions. It is widely recognized as a key enabler for digital battlefield spaces and unified operational maps.

In 2014, the Open Geospatial Consortium (OGC) established the Discrete Global Grid System Core Standard (DGGS) working group to develop the Discrete Global Grid System Core Standard 1.0. This standardizes grid system structures and functionalities, enabling interoperability between different grid systems and advancing future grid development and applications (Zhao et al., 2016). Goodchild proposed that future geographic information system (GIS) should be based on a globe rather than a planar map projection (Goodchild, 2018). The Global Grid System (GGS), developed by Canadian company PYXIS Innovation based on a hexagonal global discrete grid, has been operationalized and supports online services for the integration and real-time processing of multi-source environmental data for users. Wilfrid Laurier University in Canada has developed an Environmental Analysis and Integration System utilizing a hexagonal global discrete grid, which enables the modeling, processing, and analysis of big environmental data (Robertson et al., 2020).

In recent years, supported by the national defense 973 programs and key R&D initiatives in China, several prestigious domestic universities and research institutions have successively conducted extensive research on grid generation, giving rise to a series of representative partitioned grid systems (Guo et al., 2023; Li et al., 2006; Ma, 2006). Notable examples include Peking University's GeoSOT grid (Cheng et al., 2012), the Layered Partition Grid from the Information Engineering University (Tong et al., 2012), and the Full-Space Grid developed by the 15th Institute. Platonic solid grids employ the five regular convex polyhedrons including the tetrahedron, hexahedron (cube), octahedron, dodecahedron, and icosahedron as spherical discretization elements through inscribed polyhedral structures. This geometric approach has attracted significant research attention in computational geometry and geospatial applications. Notably, Qian et al. (2019) proposed the GeoSOT-ST grid system, an octahedron-based hierarchical spatial indexing framework that enables efficient management and querying of massive spatiotemporal trajectory datasets. Han

et al. (2025) enhanced the performance of spatiotemporal knowledge graph reasoning by integrating the GeoSOT grid with graph convolutional networks. In the domains of battlefield geographic environment modeling and military simulation, Wu et al. (2021) established combat environment models by employing H3, which is an open-source hexagonal global grid library.

Currently, the Ministry of Natural Resources and other agencies have adopted spatial grids as the foundational framework for the 3D Realistic Scene - Basic Geospatial Entity Spatial Identity Coding Rules. Military organizations also prioritize grid applications, actively promoting the development of a spatial grid application ecosystem.

The Earth spatiotemporal grid framework has rapidly advanced, achieving progress in spatiotemporal information encoding, expression, and computational methods. However, challenges persist in information association, spatial management, and planning applications, including difficulties in spatiotemporal alignment, low association efficiency, complex spatiotemporal management, and scalability limitations in spatiotemporal planning.

To address these challenges and prepare for the impending spatiotemporal data explosion, it is urgent to innovate grid-based spatial management approaches. This includes proposing new models and methods for coordinated spatial information organization and management, constructing a novel spatiotemporal information organizational framework, and resolving the critical issues of coordinating large-scale spatiotemporal data resources and spatial activity information.

4. Novel Spatiotemporal Management Model and Methods

The Earth spatial grid technology evolved from Earth planar grid technology, initially designed to address the limitations of latitude-longitude coordinate systems in describing object spatial positions and the challenges of multi-layer penetration analysis in existing GIS. Currently, researchers are actively exploring the application of Earth spatial grid technology in managing massive, multi-source, heterogeneous data by constructing a unified spatiotemporal analysis framework to enhance overall data governance (Liu et al., 2023).

Current grid-based spatial information management methods use grids as the carrier for spatial data. After processing, spatial data is stored and managed in grid cells, with various data expressing spatial positions through relative quantities to grid centers rather than traditional Cartesian coordinates. This approach, however, complicates the integration of existing coordinate systems without extensive and costly conversions, potentially leading to fragmented spatial information, loss of inherent geometric features (e.g., topological structures), and partial semantic information (e.g., precise attributes).

A spatiotemporal grid is a multi-dimensional data structure designed to capture and display data variations and distributions across spatial and temporal dimensions (Wang et al., 2023; Wu et al., 2020). Its core concept integrates spatial and temporal dimensions into a discrete, multi-dimensional, three-dimensional grid framework. The spatiotemporal grid partitions space into regular or irregular cells, each corresponding to a specific spatial region. Each cell is further subdivided into continuous or discrete time intervals, with each interval representing a specific time period.

Research on spatiotemporal grid-based spatial management has proposed a timeline-driven "scene-grid-entity" dynamic coordination approach. This model enables grid-based construction of spatial scenes, grid-based definition of spatial entities, and grid-based management of spatial activities. By constructing a spatiotemporal information grid management model, diverse and heterogeneous spatiotemporal data can be seamlessly integrated into a unified grid framework, resolving challenges in complex spatiotemporal coordination and unified management. This approach is particularly valuable for high-precision spatial planning, real-time environmental monitoring, and managing uncertain group activities in specialized domains such as special spatial coordination, national territorial planning, and smart city management. A conceptual illustration of the grid-based spatiotemporal management model is shown in Figure 1.

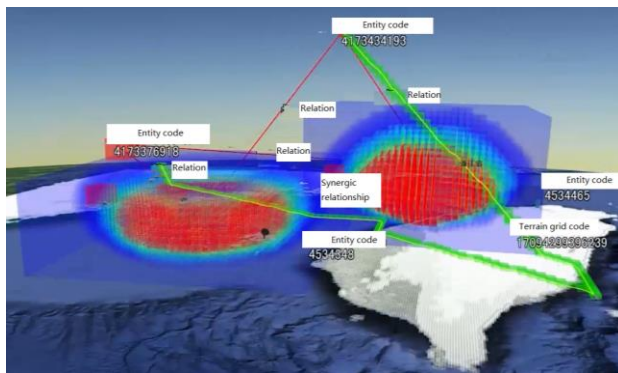


Figure 1 Conceptual Diagram of Grid-Based Spatiotemporal Management Model

Space is composed of macro-level scenes and micro-level entities within those scenes. Spatial management first involves partitioning scenes into grids, then defining static entities within grids, and finally managing entity activities over time.

4.1 Spatial Scene Grid-Based Construction

The core of spatial scene gridding lies in spatial partitioning and mapping to ensure precise spatial identification. Spatial partitioning typically employs computable, multi-level adaptable, and standardized exchangeable grid models (e.g., GeoSOT) to minimize mapping variations and computational complexity. Customized local or variable grids can be designed based on specific application needs. Spatial mapping unifies diverse scene reference systems and multi-source entity coordinate systems into an application-specific spatial reference system (e.g., the CGC2000 National Geodetic Coordinate System for Earth space) and associates them with grid models to achieve spatial mapping between location data and grid cells. A schematic of typical spatial scene gridding is shown in Figure 2.

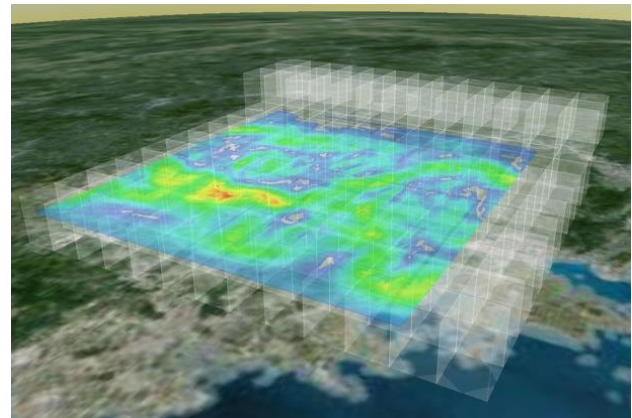


Figure 2 Schematic Diagram of Spatial Scene Gridding

Building on grid-based spatial modeling methods, spatiotemporal grids combine temporal and spatial encoding to model five basic spatiotemporal objects (coordinates, place names, time points, time intervals, and fuzzy time) and 16 basic spatiotemporal relationships (spatial topological, directional, and distance relationships; temporal precedence, coincidence, overlap, start/contain/end relationships, etc.). Convolutional calculations between grid-based spatiotemporal objects and relationships enable ubiquitous spatiotemporal semantic gridding. Ambiguous semantic fields are represented as grid sets with membership degrees, where higher membership degrees indicate stronger semantic associations.

4.2 Spatial Entity Grid-Based Definition

Spatial entity definition focuses on "grid-group entities," "grid-pack entities," and "semantic attribution to grid entities" to achieve precise mapping of real-world objects.

For entity component modeling, the grid level and geographic coordinates containing the component are first determined. Spatial mapping then identifies the grid cell location, linking the entity component to the grid. Aggregating these grids forms a grid-based entity.

Entity modeling also begins by determining corner coordinates and grid cell positions. Horizontal and vertical associations between corner grids compute the bounding cube, rapidly locating the grid cell enclosing the entity. A schematic of grid-based spatial entity modeling (e.g., a radar) is shown in Figure 3.

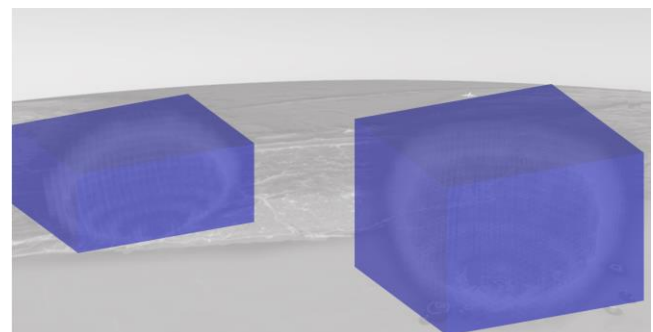


Figure 3 Schematic Diagram of Spatial Entity Gridding

Although entities and grids describe different objects—semantic content versus locational forms—they share spatial characteristics. By aligning entity semantic granularity with grid structures, grid-based entities acquire concrete semantic content.

4.3 Spatial Activity Grid-Based Management

Grid-based spatial activity management handles continuous, real-time spatiotemporal activity information, leveraging grid dynamics, autonomy, and collaboration to enable dynamic spatial grid management and resource allocation. This supports dynamic event monitoring, activity state prediction, and spatial behavior intervention.

Using activity location data and entity trajectory information, line targets are resampled to ensure distances between points are less than half the approximation precision. Rapid approximation identifies grid cell codes for the point set, extracting trajectory grid information to achieve spatial activity gridding. A schematic is shown in Figure 4.

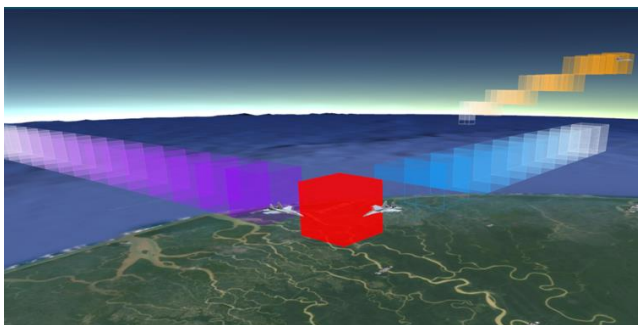


Figure 4 Schematic Diagram of Spatial Activity Gridding

(1) Spatial Scale Dynamics: Grid scales are relatively stable within time cycles but adapt dynamically to spatial activity changes, such as entity density or relationship structure shifts.

(2) Entity Management Collaboration: Entities in different spatial scenes require grid-based coordination at varying times and states to ensure activity stability and avoid spatiotemporal conflicts.

(3) Grid Autonomy: Grids are endowed with autonomous capabilities to adapt to spatial activities, triggering intelligent responses to external stimuli (e.g., electronic fences or defense channels generating alerts upon intrusion).

5. Spatiotemporal Information Organization and Management Model

By leveraging spatial and temporal attributes as foundational "handles," a spatiotemporal grid data model is developed to unify and associate urban-related data (e.g., geospatial, building, utility, power grid, and electromagnetic information). This resolves challenges in unified spatial frameworks and heterogeneous data integration, enabling comprehensive organization and management of urban information across all spatial dimensions and life cycles.

The grid-based spatial information management model organizes information through "positioning, characterization, and quantification," designing a "visible, searchable, and computable" management framework. It supports Earth-wide spatial data models spanning space, air, surface/sea, indoor, and underground/underwater domains, integrating GIS, BIM, 5G, and IoT data. All data ingestion, service distribution, and analysis are grid-scale operations.

The proposed spatiotemporal information organization framework implements three complementary strategies: (1) semantic structuring of static entity attributes, (2) hierarchical grid-based aggregation for dynamic entity states, and (3) temporal chaining of entity trajectories through networked grid indexing. This integrated approach establishes a unified model that systematically connects spatial aggregation patterns (grid-based), temporal evolution sequences (chain-structured), and contextual relationships (network-associated), as illustrated in Figure 5.

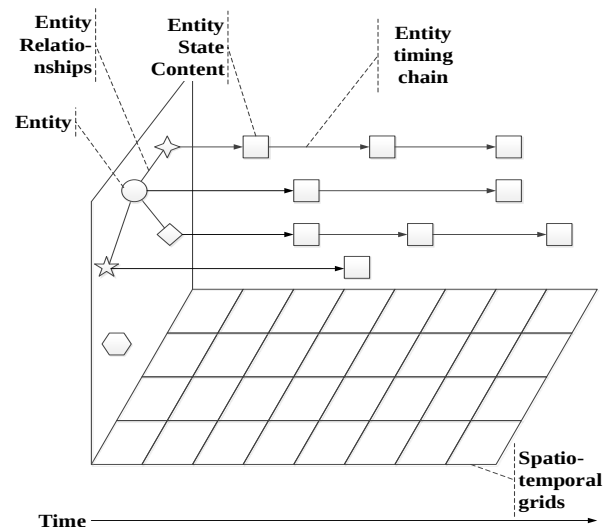


Figure 5 Structural Diagram of Spatiotemporal Information Organization Model

Spatiotemporal information comprises foundational environmental data (geospatial, meteorological, oceanographic, electromagnetic) and active entity data (entity attributes, relationships, states). Information is categorized and aggregated into spatiotemporal grids. As time progresses, entity states (position/attribute changes) are recorded via spatiotemporal grid indices, forming temporal chains.

A hybrid storage strategy combines graph databases (e.g., Neo4j) for entity semantics (attributes, relationships) and columnar distributed databases (e.g., HBase) for dynamic entity data. In columnar databases, data is stored with timestamps as sequences, grid codes as row keys, and entity identifiers as column family keys. This enables multi-phase entity management. A storage structure example is shown in Figure 6.

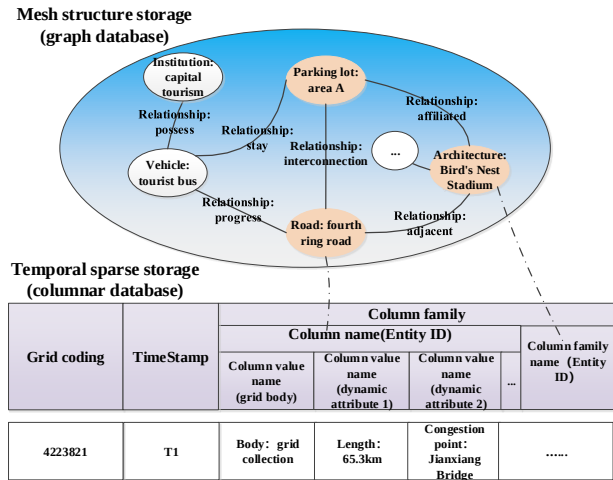


Figure 6 Structural Diagram of Spatiotemporal Information Storage Model

The grid-based spatiotemporal model supports unified management of spatiotemporal big data, heterogeneous data fusion, and multi-scale representation. It addresses bottlenecks in unifying identification, visualization, scalability, and association of massive spatial data in the IoT, big data, and cloud computing era, enabling efficient processing, retrieval, fusion, and application of information. It provides a unified framework for earth spatial computation and analysis, advancing modeling, management, and application of multi-source spatiotemporal data.

6. Conclusion

The novel spatial management model achieves structured and semantic organization of spatiotemporal data. By leveraging the spatiotemporal information management model, it effectively establishes big data associations and enables comparative analysis with traditional coordinate systems, enhancing data utility and overall efficiency.

The core of the grid-based spatiotemporal model lies in optimizing data utilization and information resource management. Future directions include standardization, intelligentization, real-time processing, cross-domain integration, and data security/privacy.

Spatiotemporal grid technology, intersecting big data, cloud computing, and AI, requires continuous innovation and R&D investment to advance core technologies. Future developments will prioritize real-time, accurate, and reliable data, while fostering cross-technology integration to drive advancements in spatiotemporal information processing and application.

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