# A Low-Altitude Data Space Framework Based on China’s National 3D Mapping Program

YIN GAO [1,2], JUN CHEN [1,2], DEHU YANG [1,3], FENGYU HAN [1], CHAOQUAN ZHANG [1]

[1] Moganshan Geospatial Information Laboratory, Huzhou, 3l3200, China
[2] National Geomatics Center of China, 100830, Beijing, China
[3] Faculty of Geosciences and Engineering, Southwest Jiaotong University, Chengdu 610031, China

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**Abstract**

The low-altitude economy has emerged as a strategic emerging industry in China, involving economic activities within airspace below 1,000 meters, such as manned/unmanned cargo/passenger transport. This three-dimensional economic form faces core challenges in ensuring flight safety, optimizing operational efficiency, and achieving large-scale commercialization, primarily due to the complexity of low-altitude environments characterized by dense urban structures, dynamic meteorological factors, and mixed aircraft operations. This demands innovative digital management solutions. A low-altitude three-dimensional data space, defined as a digitally integrated environment for organizing, managing, and applying multi-source heterogeneous data within this airspace, serves as a critical foundation for supporting safe, efficient, and intelligent development. This study proposes a comprehensive low-altitude three-dimensional data space framework grounded in China's National 3D Realistic Geospatial Landscape Model (3dRGLM). The framework establishes a spatiotemporally integrated digital environment supporting critical applications in low-altitude airspace planning, intelligent 3D navigation, and safety-guaranteed airspace management. It is structured around entity-based digital modeling of low-altitude elements, multi-source spatiotemporal data fusion via grid-discretized management, and trusted data circulation mechanisms. By leveraging 3dRGLM's capabilities in realistic 3D representation and dynamic geographic entity association, the proposed data space enables end-to-end digital twin modeling of low-altitude operational scenarios. Pilot programs in Wuhu and Deqing demonstrate the framework's effectiveness in enhancing decision-making precision for air route network design, 3D dynamic navigation, and risk-aware flight control, confirming its value as a replicable model for scalable low-altitude economy development.

## 1. INTRODUCTION

The low-altitude economy represents a transformative shift from two-dimensional surface transportation towards a comprehensive three-dimensional mobility paradigm(Chen et al., 2023b). It strategically exploits the underutilized airspace within 1000 meters of the ground, unlocking unprecedented potential for a wide spectrum of activities. These range from high-frequency urban logistics and intra-city passenger air mobility to critical emergency medical services, infrastructure inspection, precision agricultural monitoring, and aerial tourism(Liao et al., 2024). Recognized as a strategic emerging industry and a new quality productive force in China, its development is pivotal for fostering new economic growth engines, optimizing national resource allocation, and stimulating technological innovation across multiple industrial chains. However, the path to its large-scale, commercially viable, and socially integrated future is fraught with significant, interconnected challenges. The foremost hurdle is ensuring fail-safe operational safety within extraordinarily complex and dynamic urban-rural environments(Chen et al., 2025). Simultaneously, achieving high operational efficiency amidst anticipated high-density, mixed-type traffic (encompassing everything from delivery drones to air taxis) is paramount for economic sustainability(Liao et al., 2023). Underpinning both is the fundamental challenge of managing the dynamic, invisible, and infrastructure-less nature of low-altitude airspace itself, which lacks the physical guides and fixed pathways of ground transportation.

The intrinsic complexity of the low-altitude operating environment creates a unique set of management dilemmas. This domain features intricate terrain, dense and irregular building clusters that create urban canyons, highly variable micro-meteorology, and an increasingly diverse fleet of aircraft with differing performance characteristics(Chen et al., 2023b). This complexity renders traditional, static, and predominantly manual air traffic management methods, designed for structured high-altitude corridors, inadequate and even hazardous(Liao et al., 2023). Consequently, it necessitates a fundamental paradigm shift towards fully digital-intelligent control within a unified three-dimensional digital space. This new paradigm demands, as a foundational prerequisite, the comprehensive digitization of all low-altitude elements—not just static geography but dynamic objects and conditions. It further requires the capability for sophisticated, real-time 3D spatial analysis and simulation, and ultimately, a robust system for data-driven dynamic response and automated decision-making to manage the airspace at scale(Chen et al., 2025).

Addressing this national strategic need for a next-generation digital framework, China has launched its ambitious national 3D mapping program(Chen et al., 2024). The core output of this program is the 3D Realistic Geospatial Landscape Model (3dRGLM), envisioned to cover the entire country(Chen et al., 2022a). The 3dRGLM is defined as a new generation of geospatial data product, characterized by its authentic three-dimensional geometric structures, realistic visual scene rendering, and, most importantly, semantically rich and identifiable geospatial entities(Chen et al., 2024; Chen et al., 2016; Jun et al., 2004). It effectively establishes a high-fidelity digital twin of the real 3D geospatial world. This model transcends traditional mapping by serving as a next-generation spatiotemporal information infrastructure, crucial for the construction of Digital China and the broader societal digital transformation(Chen et al., 2022b). The 3dRGLM thus provides an unprecedented, unified, and realistic 3D digital framework(Fridhi and Frihida, 2019; Holland and Allan, 2001; Chen et al., 2022a). It directly offers a foundational solution to the core demand in the low-altitude economy for high-precision, entity-based, and dynamically integrable spatiotemporal information, upon which intelligent applications can be built(Chen et al., 2025; Chen et al., 2023a; Gao et al., 2024).

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This paper directly addresses the urgent and practical need to bridge the powerful capabilities of the 3dRGLM with the specific, demanding applications of the low-altitude economy. The raw 3dRGLM data product, while necessary, is not sufficient. Therefore, a dedicated, application-oriented low-altitude three-dimensional data space framework, architecturally built upon the 3dRGLM foundation is proposed. This framework is specifically designed to organize, manage, fuse, and ultimately empower the massive, multi-source, heterogeneous, and high-velocity data streams inherent to low-altitude operations. It moves decisively beyond simple 3D visualization towards enabling advanced core competencies: large-scale spatiotemporal computing, embedded artificial intelligence for spatiotemporal insight, and secure trusted data circulation among stakeholders(Soininen and Laatikainen, 2025; Chen et al., 2023a). The goal is to form the core digital infrastructure—the "operating system"—for the safe, orderly, efficient, and scalable development of the entire low-altitude economy ecosystem.

The proposed framework is engineered to systematically tackle the challenges outlined earlier. It encompasses methodologies for the holistic digitization of low-altitude elements (terrain, dynamic objects, air rules), advanced spatiotemporal data modeling for fusion and interoperability, and a suite of enabling services that cover the entire flight operation lifecycle(Bacco et al., 2024). This integrated approach ensures that the infrastructure supports not only planning and navigation but also real-time safety management and post-operation optimization, creating a closed-loop, continuously improving system for low-altitude airspace management.

The remainder of this paper is structured to provide a comprehensive exposition of this framework. Section 2 details the proposed technical framework and its constituent methodologies, explaining the "how" of the low-altitude data space. Section 3 presents experimental results and application demonstrations from pilot programs, validating the framework's feasibility and effectiveness in real-world scenarios. Finally, Section 4 provides a general discussion, synthesizes concluding remarks, and outlines promising directions for future research and development in this critical interdisciplinary field.

## 2. Method

The low-altitude three-dimensional data space framework is structured around three foundational pillars: entity-based digital modeling of low-altitude elements (e.g., terrain, air routes, meteorological data), multi-source spatiotemporal data fusion through grid-discretized management, and trusted data circulation mechanisms. By leveraging 3dRGLM ’ s capabilities in realistic 3D representation and dynamic geographic entity association, the proposed data space enables end-to-end digital twin modeling of low-altitude operational scenarios.

### 2.1 Data Acquisition and Integration

The construction of a functional low-altitude data space fundamentally begins with the comprehensive and accurate digitalization of all pertinent elements within the operational environment. The 3D Realistic Geospatial Landscape Model (3dRGLM) serves as the indispensable spatial digital base, enabling this foundational step through its core capabilities of stereoscopic reconstruction, entity-based modeling, and realistic representation. However, supporting the low-altitude economy requires extending this general-purpose 3D model to incorporate dynamic, application-specific data streams. Therefore, the data acquisition and integration process is architected to create a multi-layered digital twin, encompassing static geography, dynamic atmosphere, and real-time operational activities:

(1) **Terrain and infrastructure modeling:** This layer establishes the static, high-fidelity 3D representation of the physical world. Leveraging the 3dRGLM, it achieves high-precision modeling of terrain, buildings, and vegetation. Critically, for low-altitude safety, this base model is augmented with specialized data to identify and model key obstacles that pose risks to low-altitude flight, such as power lines, communication towers, and wind turbines. Furthermore, it digitally incorporates essential low-altitude infrastructure, including designated takeoff and landing sites, vertiports, and ground-based charging stations. This enhanced model provides the crucial geometric and semantic baseline for flight path planning, obstacle avoidance, and airspace structure design.

(2) **Dynamic meteorological data:** The low-altitude atmosphere is highly variable and directly impacts aircraft performance and safety. Thus, the static landscape model must be dynamically integrated with real-time meteorological information. This involves continuously ingesting data streams concerning wind speed, wind direction, temperature, humidity, visibility, precipitation, and turbulence. The integration of this data transforms the static 3D model into a four-dimensional (4D) spatiotemporal environment. This capability supports critical flight decision-making, allowing for route optimization to avoid hazardous weather, calculating performance limitations, and providing alerts for micro-weather phenomena that are particularly dangerous for small unmanned aerial systems.

(3) **Operational monitoring data:** This layer deals with the digitalization of real-time activities and the sensing infrastructure itself. It involves the fusion of multiple real-time data feeds from a network of sensors, drones, and ground-based systems. Key data types include: a) Positioning Data: High-frequency location and trajectory data from aircraft using GNSS, RTK, or other positioning technologies. b) Communication Data: Status and command links between aircraft and control systems. c) Surveillance Data: Information from radar, ADS-B, and other sensing modalities used to monitor aircraft position, especially for non-cooperative "black flight" detection. d) Infrastructure Status Data: Operational health data from communication, navigation, and surveillance (CNS) ground stations. The fusion of these heterogeneous feeds creates a coherent, real-time picture of the airspace's operational trend, which is the essential input for dynamic traffic management, conflict detection, and safety monitoring.

### 2.2 Spatiotemporal Data Modeling

To transform the acquired raw data into a computable, queryable, and actionable digital ecosystem, a robust three-dimensional data space architecture is proposed. This architecture is specifically designed to integrate, organize, and manage the heterogeneous data sources described in Section 2.1. It moves beyond simple data storage to establish a coherent model that encapsulates both the state and the dynamic behaviors of the low-altitude environment. The architecture is built upon three foundational and synergistic pillars:

**(1) Entity-Relationship-Event Framework**: This pillar provides the semantic and logical structure for the digital twin. All digitized low-altitude elements—whether static (e.g., buildings, landing points, air routes) or dynamic (e.g., drones, weather cells, temporary no-fly zones)—are abstracted and managed as uniquely identifiable Entities with associated attributes and lifecycles(Holland and Allan, 2001). The Relationships between these entities (e.g., spatial "is near," topological "connects to," or operational "is controlled by") are explicitly modeled, creating a rich knowledge graph. Furthermore, the framework captures Events that signify state changes or significant occurrences, such as "flight plan filed," "geofence violation triggered," or "severe weather alert issued." This ERE framework organizes the complex interdependencies and interactions within the airspace into a structured, queryable model. It enables advanced semantic searches (e.g., "find all drones within 500 meters of this sensitive infrastructure"), supports complex reasoning for scenario simulation, and provides the necessary context for intelligent, event-driven automated responses, forming the cognitive core of the digital twin.

**(2) Grid-Based Spatiotemporal Management:** To achieve computational efficiency and standardized referencing for massive, dynamic data, a discretized approach to space management is essential. This pillar employs a multi-scale spherical (or 3D volumetric) grid system that partitions the continuous low-altitude airspace into a hierarchy of non-overlapping, discrete cells, each with a unique global geocode(Cheng et al., 2016; Zhao et al., 2025). This grid-based paradigm offers several key advantages. First, it enables highly efficient data aggregation and indexing; trajectories and object locations are referenced by sequences of grid codes rather than precise floating-point coordinates, converting complex geometric computations into faster integer-based operations. Second, it facilitates standardized trajectory computation, spatial analysis, and conflict detection. Algorithms for proximity checking, density calculation, and path searching can operate directly on the grid topology, improving performance and robustness. Finally, it provides a universal spatial framework for fusing data from diverse sources that may use different original coordinate references, ensuring consistency across the entire data space.

**(3) Secure and Trusted Data Circulation**: Recognizing that the low-altitude data space is a multi-stakeholder ecosystem involving regulators, airspace managers, service operators, and end-users, enabling secure and compliant data sharing is paramount(Soininen and Laatikainen, 2025). This pillar implements a comprehensive governance and technical layer for secure data circulation. It encompasses data security protocols (e.g., encryption for data in transit and at rest) and privacy protection mechanisms (e.g., data anonymization, differential privacy) to safeguard sensitive information. Crucially, it establishes cross-domain collaboration standards and data permission models that define clear data sovereignty, usage rights, and access controls. This ensures that data can be shared and fused for collaborative applications—such as joint traffic management or emergency response—while remaining secure, auditable, and compliant with relevant regulations. This trusted environment is fundamental for fostering an open yet controlled data ecosystem that drives innovation and operational efficiency across the entire industry.

### 2.3 Spatiotemporal Empowerment Services

The constructed low-altitude three-dimensional data space transcends being a mere repository of information; it functions as an active, intelligent operational platform. Its core capability lies in the real-time integration of streaming IoT sensory data (from aircraft, weather stations, surveillance radars) and the dynamic, rule-based invocation of airspace management policies (e.g., dynamic geofencing, priority rules, congestion pricing). This creates a continuous data pipeline that drives the entire flight control operational chain, fundamentally shifting the management paradigm from static, pre-defined planning to adaptive, dynamic response. This empowered data space provides comprehensive support across the entire flight lifecycle, enabling coordinated pre-flight planning, proactive in-flight safety management, and evidence-based post-flight evaluation and optimization:

(1) **Pre-flight Integrated Planning**: This phase leverages the data space to conduct comprehensive, multi-constraint mission planning, ensuring the safe and efficient execution of flight operations before they commence. Planners and automated systems interact with the digital twin to perform integrated resource coordination. This involves: a) Dynamic Airspace Allocation: Assessing available airspace volumes against demand, reserving corridors, and defining temporary flight restrictions based on real-time constraints. b) Optimal 4D Route Generation: Calculating not just a 3D path but a 4D trajectory (including time), optimizing for factors like weather avoidance, energy consumption, noise abatement, and airspace congestion. c) Takeoff/Landing Site (Vertiport) Scheduling: Coordinating slot times and ground resource allocation at vertiports and landing zones to prevent ground congestion. d) Regulatory Compliance Check: Automatically verifying proposed flight plans against a digital rulebook of operational regulations, no-fly zones, and airspace classifications. This integrated planning process, supported by simulation and conflict detection within the data space, moves from sequential, manual checks to a holistic, automated, and optimized pre-flight preparation stage.

(2) **In-flight Safety Management and Control:** Once a mission is airborne, the data space transitions to its critical role in real-time safety assurance and dynamic traffic management. It continuously ingests live telemetry and surveillance data, enabling dynamic analysis and precise control. Key functions include: a) Real-time 3D Navigation & Conformance Monitoring: Comparing the aircraft's actual 4D trajectory against its planned path and providing guidance or alerts for deviations. b) Proactive Risk Warning: Utilizing fused data (e.g., proximity to other aircraft, sudden weather changes, intrusion into dynamic geofences) to generate predictive collision and hazard alerts. c) Capacity-Flow Matching & Dynamic Re-routing: Monitoring real-time traffic density and system capacity, automatically suggesting or implementing route adjustments to mitigate congestion and maintain overall network efficiency. d) Automated Emergency Response: In case of contingencies (e.g., vehicle failure, medical emergency), the system can instantly calculate safe landing zones, clear adjacent airspace, and coordinate with emergency services. This capability enables a shift from reactive monitoring to predictive and prescriptive safety management, ensuring operational integrity in high-density, mixed-traffic environments.

(3) **Post-flight Evaluation and Optimization:** The data space's value extends beyond the completion of a flight, serving as the foundation for a multi-stakeholder collaborative closed-loop evaluation system. By securely aggregating post-flight data (actual trajectories, energy usage, incident reports, passenger feedback) under a governed data permission model, it enables comprehensive performance analysis. This supports multi-objective collaborative optimization of the entire low-altitude traffic system across several dimensions: a) Green & Environmental: Analyzing noise footprints and emissions to


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optimize routes for community impact and sustainability. b) Safety: Conducting forensic analysis of incidents and near-misses to identify systemic risks and update safety protocols. c) Efficiency: Evaluating airspace utilization, vertiport throughput, and network delays to refine traffic flow models and infrastructure planning. d) Economic: Assessing operational costs and service reliability to inform business models and pricing strategies. This data-driven feedback loop transforms operational experience into continuous system-wide improvement, fostering a safer, greener, and more efficient low-altitude ecosystem.

## 3. Key Applications

Empirical applications demonstrate that the framework significantly enhances decision-making precision in air route network design, 3D dynamic navigation, and risk-aware flight control. For instance, in low-altitude airspace planning, it supports multi-constraint optimization incorporating building distributions, no-fly zones, and real-time meteorological factors. In navigation, it integrates high-precision positioning and electronic fence technologies to ensure operational safety.

### 3.1 Low-altitude Airspace Planning

Effective and safe utilization of the three-dimensional airspace resource necessitates its rational and structured organization, akin to the way ground transportation relies on a planned road network. Inspired by the hierarchical design principles of ground transportation networks, we propose and design a multi-level low-altitude air route system. This system is architected to categorize and manage traffic flows based on their function, range, and density. It comprises: (1) Trunk Routes: These are the high-capacity, inter-city aerial corridors designed for efficient, long-distance movement of passengers and cargo, forming the backbone of the regional low-altitude transportation network. (2) Branch Routes: Operating at an intra-regional scale, these routes connect major activity hubs, industrial parks, and logistics centers within a metropolitan area or region, distributing traffic from the trunk network. (3) Terminal Routes: These are dedicated to last-mile connectivity, providing structured access from branch routes or vertiports directly to specific delivery points, building rooftops, or emergency sites within dense urban or suburban environments.

The design and optimization of this multi-level network are conducted within the low-altitude three-dimensional data space. This enables multi-constraint optimization that simultaneously considers complex factors such as high-resolution terrain and building distributions, predefined no-fly zones (e.g., around airports, government buildings), real-time and forecast meteorological conditions, noise sensitivity areas, and existing air traffic. The digital twin environment allows planners to simulate traffic flow, evaluate safety buffers, and optimize the 3D alignment of routes for maximum efficiency and minimal community impact.

To enforce this structure and ensure safe, organized utilization, the plan leverages electronic fencing (geo-fencing) and dynamic boundary management technologies. Permanent and temporary electronic fences are digitally defined within the data space to delineate the boundaries of different route types, restricted zones, and protected areas. More importantly, dynamic boundary management capabilities allow for the real-time activation, deactivation, or adjustment of these airspace segments in response to operational needs, such as temporary events, emergencies, or shifting traffic patterns. This ensures the airspace structure is not rigid but can adapt dynamically, balancing the need for order with the flexibility required for a scalable and resilient low-altitude traffic system.

### 3.2 3D Low-Altitude Navigation

Addressing the paramount challenge of ensuring low-altitude flight safety, this research places a significant focus on the development and implementation of a specialized low-altitude 3D navigation map product. This product serves as the core spatial cognitive component for both pilots and autonomous flight systems, bridging the gap between raw geospatial data and actionable navigational intelligence.

Fundamentally, the product is built upon the high-precision foundation of real-scene 3D data provided by the 3dRGLM. This base is then semantically enriched and functionally augmented through the integration of multiple critical, application-specific data layers. These layers include: (1) a comprehensive and dynamically updated obstacle layer detailing structures like power lines, towers, and buildings with enhanced geometric accuracy; (2) a verified takeoff/landing sites layer containing information on vertiports, helipads, and emergency landing zones, including their operational status, physical dimensions, and booking availability; (3) the structured air route network layer, encompassing the digitally defined trunk, branch, and terminal routes; and (4) a communication, navigation, and surveillance (CNS) facilities layer that provides metadata on the location, type, and coverage of ground-based support infrastructure. This integration creates a unified, authoritative digital chart for the low-altitude domain.

The product is designed to be more than a static map; it is an intelligent, connected data service. It supports core functions such as 3D route planning and optimization that consider aircraft performance, weather, and dynamic restrictions. It enables real-time positioning and conformance monitoring by fusing onboard GNSS/INS data with the map's high-integrity features. Crucially, it provides context-aware alerts and guidance for obstacle proximity, airspace boundary (geofence) adherence, and conflict detection.

Demonstrations conducted in pilot locations such as Deqing and Wuhu have been instrumental in validating this product's practical utility. In these tests, the 3D navigation map was deployed to support specific use cases like unmanned logistics delivery and emergency response operations. The outcomes validated its effectiveness in enhancing situational awareness, enabling precise navigation in complex environments, and contributing to overall operational safety. These pilots aim to solidify technical specifications, refine production workflows, and support the maturation and growth of the emerging low-altitude 3D navigation industry by providing a proven, scalable model for next-generation aerial navigation solutions.

### 3.3 Low-Altitude Digital Infrastructure

The sustainable and scalable development of the low-altitude economy necessitates a robust, foundational digital layer—a Low-Altitude Digital Infrastructure. This infrastructure, conceptualized as the low-altitude digital base, is far more than a simple platform; it is a comprehensive, systemic framework designed to be the core "operating system" for the entire sector. It is fundamentally built upon the authoritative, high-fidelity foundation of real-scene 3D information (3dRGLM) and is deeply integrated with new-generation digital technologies, most notably low-altitude spatiotemporal big data analytics,

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artificial intelligence, the Internet of Things (IoT), and cloud-edge computing. This integration transforms raw geospatial data into an intelligent, proactive, and service-oriented ecosystem. The architecture of this digital base is organized into four interconnected core modules:

**(1) Spatiotemporal Data System**: This module constitutes the "data refinery," encompassing the low-altitude three-dimensional data space discussed throughout this paper. It is responsible for the unified acquisition, fusion, management, and trusted circulation of all heterogeneous data, serving as the single source of truth for the digital twin.

**(2) Smart Technology System**: This module acts as the "brain," comprising the algorithms, models, and computational engines. It integrates capabilities for AI-powered perception (e.g., object detection from video streams), spatiotemporal computing (e.g., trajectory prediction, conflict resolution), simulation, and knowledge graph reasoning, enabling the extraction of insights and intelligence from the data system.

**(3) Service Enablement System**: This module functions as the "nervous system," providing standardized, scalable, and secure Application Programming Interfaces (APIs) and software development kits (SDKs). It exposes the capabilities of the data and technology systems as reusable services—such as airspace status query, flight plan filing, dynamic geofencing, and navigation updates—to upper-layer applications.

**(4) Standards and Specifications System**: This module provides the essential "rules and protocols," ensuring interoperability, security, and quality across the ecosystem. It includes technical standards for data formats, communication protocols, service interfaces, and safety and security specifications, fostering an open and collaborative industrial environment.

This integrated quadruple-module framework is supported by underlying information system infrastructure (cloud computing, edge nodes, communication networks), as well as a coherent set of policies and regulations that govern its use. Operating via secure government internal and external networks, it delivers multi-level, multi-dimensional services to all stakeholders: managers (e.g., regulators for oversight and dynamic control), operators (e.g., logistics companies for fleet management and optimization), and consumers (e.g., end-users for service access). Ultimately, this low-altitude digital infrastructure aims to de-silo operations, lower innovation barriers, and provide a unified foundation for the safe, efficient, and prosperous growth of the low-altitude economy.

## 4. Results and Discussion

To empirically validate and demonstrate the practical viability of the proposed integrated framework—encompassing low-altitude three-dimensional data space construction, intelligent airspace planning, 3D navigation, and digital control—pilot programs were systematically designed and executed. These programs were conducted in two selected, geographically and functionally distinct regions: Wuhu City in Anhui Province and Deqing County in Zhejiang Province (Figure 1). The primary objective of these experiments was to stress-test the technical components in real-world settings, evaluate the framework's operational efficacy, and, ultimately, establish a replicable and scalable model for low-altitude economy development that can be adapted to diverse urban, suburban, and rural contexts across Chin.

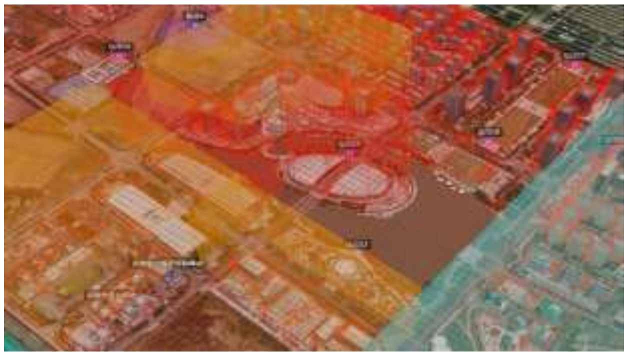

**Figure 1.** The low-altitude three-dimensional data space based on 3dRGLM

The pilot in Deqing was strategically designed to address the challenges of multi-level air route network planning and dynamic airspace management within a region featuring complex topography that blends urban centers, mountainous areas, and scenic countryside. This environment, coupled with growing low-altitude logistics demands (e.g., tourism, agricultural monitoring, emergency material transport), served as an ideal testbed. The implementation involved building a localized 3D data space by integrating Deqing's real-scene 3D data, a meticulously compiled obstacle database (including power lines and communication towers in rural areas), and models of existing communication-navigation-surveillance infrastructure. Utilizing this digital foundation, a structured low-altitude traffic system was designed, featuring dedicated corridors for logistics drones and scenic tourism routes. The pilot successfully demonstrated dynamic airspace management; for instance, temporary no-fly zones (electronic fences) could be activated around special events in real-time, and traffic flow was monitored and adjusted based on live demand. The key takeaway from Deqing was the validation of the framework's ability to bring order and safety to low-altitude operations in topographically complex regions, proving that structured "skyways" are both feasible and necessary for mixed-use airspace (Figure 2).

**Figure 2.** Deqing's Low-altitude Airspace Planning

In contrast, the Wuhu pilot concentrated on the development, testing, and application of a low-altitude 3D navigation map product as a core enabling technology. The work here focused on creating a high-integrity navigation data product by integrating centimeter-to-decimeter level precision terrain and city modeling from the 3dRGLM with real-time meteorological data feeds and dynamically configurable electronic fence technologies. This integrated 3D map was then deployed to support concrete operational demonstrations. These included unmanned cargo delivery routes between logistics hubs and urban distribution points, and simulated emergency response operations (e.g., medical specimen transport) in Wuhu's mixed urban-rural environments. The demonstrations provided critical validation on several fronts: the accuracy and reliability of the 3D navigation map for path planning and obstacle avoidance, the effectiveness of real-time data integration for in-flight decision support, and the practical utility of the entire system for specific business and public service scenarios (Figure 3). The Wuhu pilot thus served as a crucial step in maturing the productization pipeline for low-altitude 3D navigation and showcased its indispensable role in enabling beyond-visual-line-of-sight operations.

**Figure 3.** Wuhu's low-altitude three-dimensional navigation system

These coordinated, yet distinct, pilots have yielded more than isolated success stories. Collectively, they have established invaluable references for ongoing and future national standardization efforts. The practical experience gained in data specification, air route classification, 3D map data models, and system interoperability directly informs the drafting of technical standards and regulatory guidelines. Furthermore, the pilots provided critical practical insights for optimizing the broader technical framework and operational protocols. For example, they highlighted the importance of ultra-low-latency data pipelines for dynamic control, the need for standardized data interfaces between different manufacturers' ground control stations and the central data space, and the optimal update frequencies for different data layers within the 3D navigation map (Figure 4).

**Figure 4.** Deqing's low-altitude three-dimensional management and control system

The successful implementation in two geographically and economically distinct regions—Deqing with its terrain complexity and Wuhu with its focus on urban-rural integration—provides strong, early evidence for the scalability and adaptability of the proposed low-altitude digital infrastructure system. It demonstrates that the core framework is not a one-size-fits-all solution but a flexible architecture that can be configured to meet local priorities and constraints.

While the drones confirm foundational feasibility, the journey towards a nationwide, high-density low-altitude economy requires significantly scaled validation. Future work will therefore intensively focus on practical validation and demonstration through larger-scale, more complex flight operations. This includes, but is not limited to: 1) Conducting long-endurance, networked operations involving dozens of simultaneous aircraft in a single region to stress-test traffic management algorithms and communication systems. 2) Integrating the low-altitude data space with other urban digital infrastructures (e.g., smart traffic management systems) to achieve genuine air-ground integration. 3) Advancing the level of automation and artificial intelligence within the system, moving from decision support towards predictive traffic management and autonomous conflict resolution. 4) Expanding pilot regions to include megacities, major transport hubs, and ecologically sensitive areas to understand and address an even broader set of challenges. This iterative process of scaling from pilot to regional and eventually national implementation will be essential for transitioning the low-altitude economy from a strategic vision into a safe, efficient, and ubiquitous reality.

## 5. Conclusion

While the pilot programs in Wuhu and Deqing confirm the foundational technical and operational feasibility of the proposed framework, the journey towards a nationwide, high-density, and commercially robust low-altitude economy necessitates validation at a significantly larger scale and complexity. The confined, controlled environments of initial pilots must give way to stress tests under real-world conditions of scale. Therefore, future work will intensively focus on phased, practical validation and demonstration through increasingly larger-scale and more complex integrated flight operations. This critical next phase includes, but is not limited to, the following interconnected research and development thrusts:

**(1) Conducting High-Density, Networked Endurance Operations**: Future demonstrations must evolve beyond single or few aircraft scenarios to involve the coordinated, simultaneous operation of dozens, and eventually hundreds, of diverse aircraft (e.g., logistics drones, air taxis, inspection craft) within a single metropolitan region. These operations will serve as the ultimate stress test for core system components. They will rigorously evaluate the scalability and robustness of traffic management algorithms under peak load, the resilience and latency of the underlying communication and data link systems (including 5G/6G and satellite-based connectivity), and the effectiveness of the low-altitude data space in maintaining a coherent, real-time picture of the entire network amid high data velocity and volume.

**(2) Achieving Genuine Air-Ground Integration**: The low-altitude economy does not exist in a vacuum; it is intrinsically linked to terrestrial urban systems. A pivotal focus will be on seamlessly integrating the low-altitude data space with other critical urban digital infrastructures. This involves establishing bidirectional data exchanges and shared operational protocols with smart traffic management systems to coordinate aerial and ground vehicle flows at intersections and logistics hubs, with urban information models (CIM) for holistic city management, and with public safety and emergency response platforms. This integration is essential for optimizing city-wide resource allocation, managing multimodal journeys, and ensuring public safety during complex operations.

**(3) Advancing System Automation and Artificial Intelligence**: The current framework provides strong decision support. The next evolutionary step is to enhance the system's autonomous intelligence. This entails advancing the level of automation and AI within the data space and control modules. The goal is to progress from reactive alerts and human-in-the-loop decisions towards predictive traffic management (anticipating congestion and proactively mitigating it) and autonomous conflict resolution (where the system can compute and negotiate safe, optimized de-confliction maneuvers in real-time with minimal human intervention). This requires breakthroughs in machine learning for trajectory prediction, multi-agent negotiation algorithms, and explainable AI for regulatory trust.

**(4) Expanding to Diverse and Challenging Geographic Contexts**: To prove true adaptability, the pilot scope must expand beyond the initial test regions. Future pilot regions should deliberately include megacities with extreme urban canyon effects and dense population, major multimodal transport hubs (e.g., international airports, high-speed rail stations) where integration complexity is highest, and ecologically sensitive areas where the environmental and noise impact of operations must be meticulously managed. This expansion is crucial to understand, model, and address a vastly broader set of technical, social, and environmental challenges, ensuring the framework's solutions are universally applicable and resilient.

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