Construction and Integration of Image Control Point, Interpretation Sample, and Spectral Information Databases for Megacity Management

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Abstract

With the rapid advancement of satellite, aerial, and UAV platforms, the daily volume of remote sensing data collected over megacities has grown exponentially. However, only a limited portion of this data can be transformed into usable products in time. Current production workflows remain lengthy and poorly automated, which fails to meet the increasing demand for high-precision and high-timeliness remote sensing products in city management, environmental monitoring, and emergency response.

To address this gap, this study proposes the construction of an standardized, efficient and reusable foundational database system consisting of three key components: image control point database, interpretation sample database, and spectral information database. The image control point database establishes a unified geometric reference for multi-source data; The interpretation sample database provides large-scale, high-quality labeled data for deep learning-based image analysis; and the spectral database offers standardized spectral features for accurate classification and parameter inversion.

Together, the three databases form a collaborative mechanism that links geometric accuracy, semantic understanding, and spectral consistency, thereby building a complete chain from analysis-ready data (ARD) production to rapid information extraction. Using Shanghai as a case study, this paper presents the design, construction, and collaborate applications of the three databases, demonstrating their effectiveness in supporting refined and sustainable megacity governance.

1. Introduction

The exponential increase of high-resolution remote sensing (RS) data has expanded urban observation capabilities while simultaneously exposing bottlenecks in transforming raw data into actionable information (Yu et al., 2023, Chen et al., 2024, Tokarczyk et al., 2015). Many workflows still operate case-by-case, repeating geometric correction, manual interpretation, and analysis per dataset, leading to inefficiencies and limited scalability (Ma et al., 2024, Toutin, 2004).

What’s more, the absence of data accumulation and reuse arises from redundant data generation across departments and disordered data management practices. To address these issues, a database-based storage and management framework is adopted, ensuring systematic data organization, reusability, and interoperability for large-scale remote sensing applications.

In this study, we introduce an integrated, foundational data infrastructure that is crucial for city-scale automation and intelligence. We identify three pillars:

1. **Image Control Point Database (ICPD)** for unified geometric alignment and reference consistency.
2. **Interpretation Sample Database (ISD)** for semantic understanding via labeled samples supporting AI models.
3. **Spectral Information Database (SID)** for standardized spectral signatures enabling physically grounded classification and inversion.

This paper outlines the architecture, construction, and collaboration of these databases and presents a real-world Shanghai case study.

2. Overall Framework

Figure 1 illustrates the collaborative architecture of three-databases. The production chain proceeds through:

1. **Geometric Alignment:** A unified geometric reference is provided by image control points stored in the ICPD, enabling the co-registration of multi-source imagery and the efficient production of spatially and temporally consistent ortho-images. These ortho-images then serve as a stable base for ISD- and SID-based semantic and spectral analyses in continuous urban and environmental monitoring (Han et al., 2018).
2. **Semantic Labeling:** Large numbers of high-quality labeled samples enable AI models to learn diverse urban patterns, improve recognition accuracy, reduce false alarms, and generalize better across tasks such as land-cover classification, object detection, semantic segmentation, and change detection (Zhu et al., 2020).
3. **Spectral Information:** Spectral features characterize the physical properties of surface materials. They can be used to derive quantitative information such as material composition or vegetation status and cross-check and refine interpreted results (Kumar et al., 2020).

The three databases operate in an integrated manner. The Image Control Point Database integrates geometric information, including XYZ coordinates, descriptive attributes, and small control-image blocks. This creates a unified geometric reference for subsequent data production. Using this reference, multi-source raw remote sensing imagery is corrected and fused into consistent ortho-images and hyperspectral products. The ortho-images provide the spatial foundation

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for building the Interpretation Sample Database, which contains high-quality semantic samples for land-cover mapping, land-use interpretation, object detection, change detection, and scene understanding. In parallel, hyperspectral imagery and field spectral measurements feed into the Spectral Information Database, which stores spectral signatures of soil, vegetation, artificial surfaces, and water bodies. Together, the ISD and SID supply complementary semantic and physical information, enabling robust, multi-task urban and environmental analysis within a common reference framework.

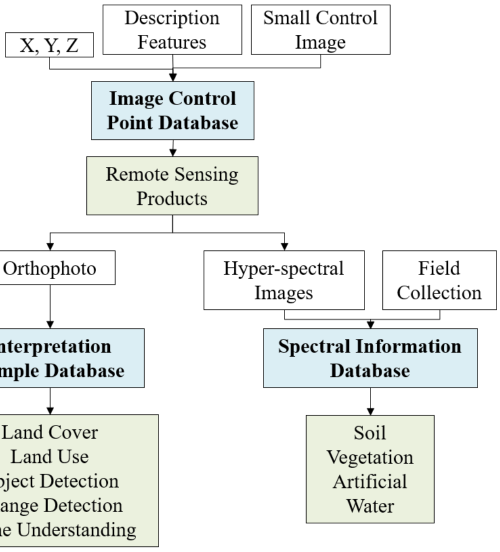


Figure 1. Proposed three-database collaborative framework linking geometric alignment (ICPD), semantic labeling (ISD), and spectral validation (SID).

3. Construction of the Three Databases

3.1 Image Control Point Database (ICPD)

3.1.1 Scope and Sources The ICPD serves as the foundational layer for geometric correction in ortho-image production. It is designed to provide a unified, high-accuracy, and reusable reference for multi-source imagery (Benz et al., 2022).

The database covers image control points collected for **satellite**, **aerial**, and **UAV** imagery production at different levels of measurement accuracy. It integrates control points from diverse production projects, consolidating previously collected point data to avoid redundant field measurements and improve efficiency. During subsequent production, existing high-precision points can be directly retrieved and applied in geometric correction, while lower-accuracy or outdated points can serve as references for planning new measurements.

Furthermore, the ICPD incorporates a dynamic update mechanism to ensure data validity over time. Given that urban construction, road expansion, and surface changes may cause positional shifts or disappearance of control points, the database maintains continuous monitoring and version tracking to identify, update, or retire obsolete points. Each control point record is associated with explicit timestamps for creation and last modification, as well as status flags indicating whether a point is active, deprecated, or replaced. Historical versions are preserved, enabling users to trace the evolution of control points, reproduce past products, and perform temporal consistency analysis on the underlying geometric reference. The spatio-temporal pattern of invalidated control points can be used as an auxiliary indicator for detecting areas of urban change and for evaluating the long-term stability of the geometric reference framework.

3.1.2 Data Model and Metadata The ICPD adopts a unified data model designed to ensure structural consistency, traceability, and interoperability across multiple acquisition sources. The database is divided into three tables corresponding to data origin: satellite, aerial, and UAV. So that each record retains clear provenance and source-specific precision indicators.

Each control point entry contains three main components:

1. **Spatial information:** three-dimensional coordinates (X, Y, Z) stored in multiple coordinate systems. For satellite imagery, the elevation value is derived from a 5m resolution DEM to ensure vertical consistency.

2. **Textual metadata:** descriptive attributes such as point identifiers, naming conventions, acquisition date, point class, direction, data source, update history, and collection organization. These metadata fields provide the semantic linkage necessary for efficient indexing, filtering, and long-term data maintenance.

3. **Auxiliary image information:** composed of two types of image blocks as well as field photos. Matching blocks are extracted at a standardized size to ensure that a stable set of distinctive surrounding features is included, thereby supporting automatic image matching and geometric correction. Instruction blocks are designed to clearly represent the detailed location of the control point for manual stereo observation; a crosshair is overlaid to indicate the exact control-point position. Field photographs are further included as supplementary references for interpretation and on-site verification.

This structured data model facilitates standardized storage and rapid retrieval across heterogeneous sources. By integrating geometric, descriptive, and visual components, the ICPD ensures that every control point is both machine-readable and human-verifiable, forming a robust foundation for automated geometric correction and ortho-image production.

3.1.3 Quality Control Before being added to the ICPD, all data sources are first transformed into a unified coordinate and elevation reference system. For each record, metadata such as data source, acquisition time, accuracy indicators, and review information are documented in detail. This procedure establishes a complete and traceable quality control loop, ensuring that every dataset within the ICPD is verifiable, reproducible, and suitable for reliable geometric correction and large-scale production.

After data are stored, regular update inspections are conducted to verify the validity of each control point. The process involves checking whether the corresponding ground features have changed or disappeared over time due to urban construction or surface modification. When significant changes are detected, the affected points are flagged for re-measurement or replacement to maintain the database’s long-term accuracy and reliability.

3.2 Interpretation Sample Database (ISD)

The ISD is established based on the long-term accumulation of remote sensing imagery and monitoring production data. It provides standardized, reusable labeled samples to support intelligent interpretation across multiple remote sensing tasks. The ISD is designed to reflect the spatial, temporal, and functional characteristics of megacities (Taubenböck et al., 2012) and is organized around five major interpretation categories: land cover, land use, object recognition, change detection, and scene understanding (Anderson et al., 1976, Cheng et al., 2024, Yang et al., 2022, Li et al., 2022). Together, these categories provide a data foundation for AI-assisted remote sensing interpretation and urban analysis.

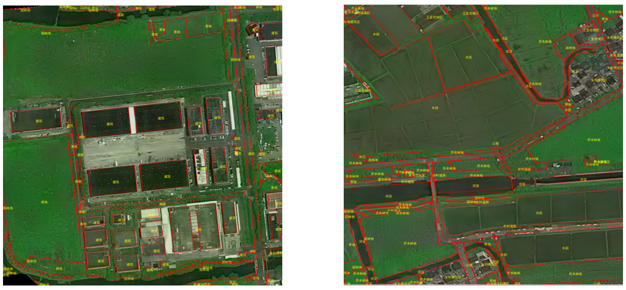
3.2.1 Data Composition The ISD consolidates labeled samples derived from previous monitoring projects, curated manual annotations, and semi-automatic extraction pipelines. Samples are stored in multiple formats, including vector polygons(.json and .shp), raster masks (.png), and image tiles (.tif), each aligned to task-specific schemas such as classification, detection, segmentation, and temporal change analysis. Reference datasets such as national geographic condition products, topographic maps, and urban land-use inventories are used directly as sample sources or spatial guides: they indicate where target objects are located in the imagery, allowing operators to efficiently delineate large numbers of interpretation samples without manually searching for candidates across the entire scene.

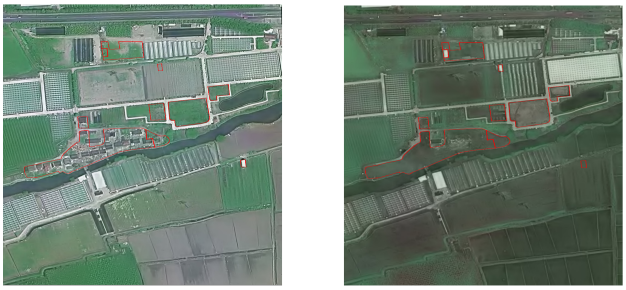
3.2.2 Classification Framework There are five main categories as shown in Figure 2:

- **Land Cover:** focuses on detailed surface material characterization (e.g., vegetation, water, impervious surfaces), emphasizing universality and scalability.
- **Land Use:** describes the socioeconomic functions of land parcels, aligned with the national land survey framework and refined for megacity land-use structures.
- **Object Recognition:** targets objects with distinctive geometry or function (e.g., buildings, vehicles, wind turbine), supporting facility census, infrastructure monitoring, and event detection.
- **Change Detection:** identifies how land cover changes over time by comparing images from different dates, providing direct evidence of surface transformation for monitoring and management.
- **Scene Understanding:** enables semantic interpretation of complex urban functional zones, forming the basis for large-scale remote sensing foundation models.

3.2.3 Quality Control and Validation To ensure accuracy and reliability, all sample polygons undergo a rigorous multilevel quality inspection process before integration into the ISD. For previously validated monitoring products, at least 10% of the polygons are randomly sampled for re-verification, while newly delineated polygons undergo 100% full inspection. Each sample is checked for accurate boundaries, category labels, and alignment with the underlying imagery.

Comprehensive topological and geometric consistency checks are conducted to detect and correct self-intersections, fragmentation, holes, and unclosed geometries. All data are stored under


(a) Land Cover (b) Land Use


(c) Change Detection (Previous) (d) Change Detection (Current)


(e) Scene Understanding

Figure 2. Examples of interpretation samples representing the five major categories

a unified coordinate reference system to maintain spatial alignment with imagery. Additionally, polygons located in cloud-covered, shadowed, or blurred regions are excluded to ensure interpretability and training quality.

3.3 Spectral Information Database (SID)

The Spectral Information Database (SID) integrates and organizes multi-source spectral data to support fine-grained classification, quantitative inversion, and material identification in remote sensing applications. According to the data acquisition source, the SID includes two main categories: **image-based spectra** and **ground-measured spectra**.

3.3.1 Data Sources Image-based spectra are obtained from three platforms—satellite, airborne, and UAV hyperspectral imagery—covering different spatial resolutions and observation angles. Ground-measured spectra include two acquisition modes: satellite-ground synchronous measurements, which are conducted simultaneously with satellite overpasses for calibration and validation purposes, and typical surface measurements, collected in the field using portable spectrometers.

3.3.2 Classification Framework The SID covers four major surface material categories: vegetation, water bodies, soil, and artificial surfaces. To build a comprehensive spectral database adapted to local conditions, field surveys and prior knowledge analyses are conducted across multiple regions and seasons. The classification framework follows the principle of “administrative division + seasonal dynamics + functional attributes”, forming a spectral dataset characterized by full spatial coverage, complete temporal cycles, and comprehensive surface types.

3.3.3 Sub-database Design

- **Vegetation Spectral Sub-database:** Spectra are collected according to district characteristics and dominant crop types, covering forests, grasslands, wetlands, and agricultural vegetation.
- **Water Spectral Sub-database:** Designed from two perspectives: (a) water quality, classified into five grades according to the Environmental Quality Standards for Surface Water (GB 3838-2002) (Ministry of Ecology and Environment of the People’s Republic of China, 2002); and (b) river distribution characteristics, with spectra collected from major river sections across different seasons.
- **Soil Spectral Sub-database:** Sampling considers regional geographical and land-cover conditions, aligned with the Classification and codes for Chinese soil (GB/T 17296-2009) (Standardization Administration of the People’s Republic of China, 2009). Major soil types include coastal saline soil, tidal soil, yellow-brown soil, and paddy soil.
- **Artificial Surface Spectral Sub-database:** Spectra are collected from various man-made structures such as residential buildings, transportation facilities, industrial complexes, agricultural installations, and other special-purpose objects.

3.3.4 Temporal Coverage To capture seasonal variation and ensure temporal representativeness, spectra are acquired periodically: at least four times per year for vegetation and water bodies, twice per year for soils depending on cropping conditions, and once per year for artificial surfaces. The specific acquisition schedule is adjusted according to meteorological conditions and satellite overpass timing to ensure consistent data quality.

3.3.5 Quality control As for quality control, a multi-stage process should be applied. Redundant measurements should be collected to test spectral stability and repeatability, metadata should be checked for completeness and consistency, and spectra that are clearly abnormal compared with normal ranges or expected patterns should be flagged through basic physical and statistical screening. These steps help ensure the reliability and usability of the Spectral Information Database.

3.3.6 Data Processing All spectral data undergo standardized preprocessing, calibration, and normalization before being archived in the SID to ensure consistency and interoperability across sources.

Overall, the SID provides a high-quality, multi-temporal, and multi-source spectral knowledge base that supports accurate spectral matching, material identification, and quantitative analysis for megacity-oriented remote sensing applications.

4. Collaborative Mechanism of the Three Databases

The Image Control Point Database, Interpretation Sample Database, and Spectral Information Database are designed as a spatially aligned and mutually reinforcing system. Together, they form an integrated framework that links geometric calibration, semantic interpretation, and spectral validation, enabling seamless transformation of raw imagery into products. This collaboration significantly enhances automation, accuracy, and scalability in remote sensing production.

Geometric Foundation Megacities require high-frequency, fine-grained monitoring, which in turn imposes very high demands on the geometric accuracy, stability, and timeliness of ARDs. The ICPD provides a unified spatial reference that ensures all datasets like satellite, aerial, and UAV imagery are geometrically consistent. Each control point is measured through standardized procedures tailored to different platforms: satellite ICPs are extracted from high-quality reference ortho-images using image-based measurement rules, while aerial and UAV ICPs are obtained via GNSS–RTK field surveys or derived from high-precision LiDAR point clouds, real-scene 3D models and stereo image pairs. These well-distributed, high-accuracy control points serve as the geometric anchors in photogrammetric workflows. During sensor model optimization, block triangulation and bundle adjustment, the ICPD enables robust geometric alignment across scenes. As a result, the ICPD supports the efficient production of spatially and temporally unified ortho-images and oblique 3D models, ensuring that all downstream datasets share a consistent and reliable geometric foundation. This eliminates cross-sensor spatial discrepancies and enables the ISD and SID to operate within a unified spatial reference framework for multi-source image correction, fusion, and co-registration.

Semantic Enhancement Megacity management requires remote sensing interpretation at very high temporal frequency and across massive data volumes, making manual inspection nearly impossible to sustain. In this context, AI-based interpretation models are essential for automating large-scale monitoring and analysis, but they can only perform reliably in local operational environments if they are trained on representative, high-quality samples. The ISD addresses this need by providing rich semantic annotations for land-cover categories, land-use functions, object classes, and change dynamics within the unified geometric framework established by the ICPD. Because the samples are derived from the local urban environment, they capture city-specific spectral-textural characteristics and morphological patterns that are often missing from generic global datasets. Such locality is critical for achieving robust model performance in megacity applications, where object density, landscape composition, and intra-class variability differ markedly from those in common open-source benchmarks.

Each sample is stored with precise geographic coordinates, enabling spatially aligned multi-modal learning. Image patches can be directly paired with co-registered Digital Elevation Models (DEMs), Digital Surface Models (DSMs), LiDAR point clouds, vector data, and other auxiliary modalities, supporting the development of coordinate-aware neural architectures that fuse 2D and 3D information (Zhuang et al., 2021, Zou et al., 2021). Furthermore, ISD semantic labels can be cross-referenced with spectral signatures in the SID to disambiguate confusing classes and enhance model performance through the joint exploitation of semantic and physically based information.

Spectral Validation Megacity management places strong emphasis on ecological protection, requiring continuous monitoring of vegetation dynamics, water quality, and the spatial integrity of urban green-blue infrastructure (Budzik et al., 2024, Degerickx et al., 2020). The SID provides a spectral foundation by offering physically meaningful measurements, such as reflectance curves, band ratios, and spectral indices, that characterize the optical properties of surface materials.

These measurements support quantitative assessment of vegetation condition, canopy vigor, soil properties, and water quality. Spectral indicators sensitive to chlorophyll, biomass, leaf moisture, and turbidity enable fine-scale ecological monitoring and long-term environmental evaluation. They also improve material discrimination and provide a robust basis for quantitative inversion in environmental applications. When combined with ISD-derived land-cover and land-use semantics, the SID further strengthens ecological interpretation and supports data-driven environmental management in megacity contexts.

Integrated Workflow The three databases operate jointly to form a workflow: the ICPD ensures geometric consistency and alignment; the ISD provides semantic structure and interpretive context; and the SID supplies physical and spectral validation. Because all datasets are spatially registered within the same coordinate reference system, they can be used jointly and seamlessly for multi-source data fusion, model training, and automated product generation. This collaborative mechanism lays the foundation for high-precision, intelligent remote sensing applications in megacity environments.

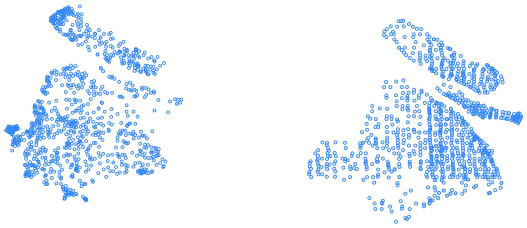
5. Case Study: Shanghai

We deploy the system in Shanghai, a megacity with complex urban form and diverse landscapes. Located in a low-lying coastal delta, Shanghai contains dense river and canal networks, extensive built-up areas, and fragmented green-blue spaces. The city includes old urban cores, industrial zones, high-density residential areas, transportation corridors, and rapidly expanding peri-urban areas, which together create strong spatial heterogeneity and frequent land-use change. As a national center of economy and governance, Shanghai has strong needs for monitoring land resources, urban development, ecological protection, and emergency response. These characteristics make Shanghai an ideal testbed for evaluating the scalability, robustness, and practical value of the proposed three-database framework in real-world megacity management.

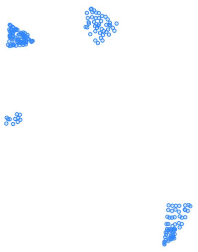
5.1 Data Summary

Shanghai was selected as the pilot area to evaluate the construction and collaborative application of the ICPD, ISD, and SID. The integrated system supports multi-scale image production, interpretation, and validation for complex urban environments.

5.1.1 Image Control Point Data The ICPD includes more than **3,500** satellite image control points, **1,500** aerial image control points, and **300** UAV iamge control points. The distribution is shown in Figure 3. These points serve as the geometric foundation for producing ortho-images at multiple resolutions: citywide 0.5 m satellite ortho-images generated at least quarterly, 0.1 m aerial ortho-images produced annually, and centimeter-level UAV imagery and 3D models for local refinement and validation.



(a) Satellite ICPs (b) Aerial ICPs



(c) UAV ICPs

Figure 3. Distribution of ICPs across the three databases (satellite, aerial, and UAV).

5.1.2 Interpretation Sample Data The ISD contains a large-scale collection of labeled image samples exceeding **300,000** image patches at the size of 1024*1024 pixels.

These samples provide semantic and temporal diversity, supporting multi-level AI training and benchmarking for urban-scale remote sensing interpretation. Coordinate-aligned satellite image, aerial images and UAV images are used.

5.1.3 Spectral Information Data The SID integrates both image-derived and ground-measured spectra to support quantitative remote sensing applications. It comprises data from

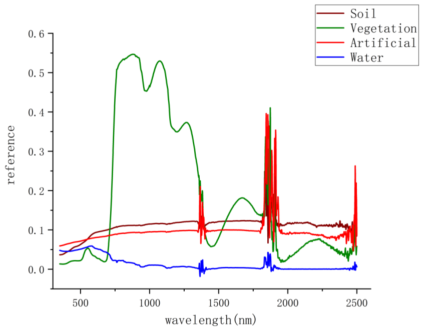


Figure 4. Spectral reflectance characteristics of four surface categories: soil, vegetation, artificial targets, and water.

20 satellite-ground synchronous measurement zones and 210 field sampling sites, covering four major surface categories: vegetation, soil, water bodies, and artificial targets. In total, **32,373** spectral sampling points were extracted from remote sensing imagery, while **1,890** ground-measured spectral curves, as shown in Fugure 4, were collected at the 210 field sites.

5.2 Functions

5.2.1 ICPD Following the establishment of the multi-source Image Control Point Database (ICPD), a complete application workflow has been implemented, including data acquisition, database integration, and result generation. To enable operational deployment and public accessibility, dedicated software systems have been developed to support end-to-end database interaction. The ICPD system provides four major functional modules: data entry, data browsing, data export, and intelligent spatial filtering.

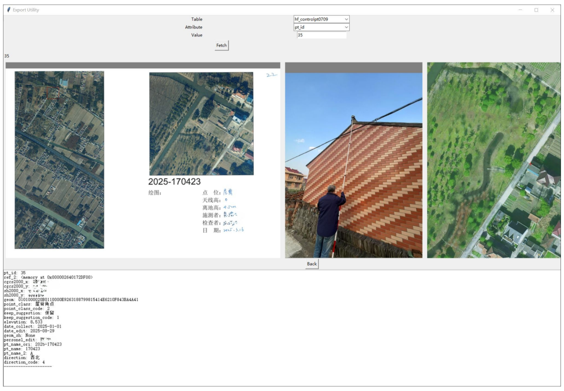
The data entry module allows automated batch import of spatial coordinates, image thumbnails, and associated attributes for satellite, aerial, and UAV control points. The attribute annotation module displays pre-cropped image blocks together with the basic information for each ICP. Operators manually mark signals at control-point locations on the image blocks and assign descriptive attributes, ensuring consistency between the spatial and textual information.

The data browsing module supports queries by control-point ID, name, and other attributes. It also visualizes the corresponding image blocks for direct inspection and quality validation, as shown in Figure 5.

The data export module is developed with SQL and PostGIS. It supports multiple export options, including point ID, image bounding box, coordinate range, and user-defined polygons (Shapefile). Advanced users can also write custom SQL statements for specific queries (Figure 6). Exported results are provided in CSV and SHP formats for direct use in photogrammetric and GIS workflows.

The intelligent spatial-filtering module can export uniformly distributed image control point subsets. It applies clustering based on a user-defined distance threshold to group nearby points. For each cluster, the best point is selected for export. The selection is ranked by acquisition time, positional accuracy, and preservation priority.

With database support, operators can filter ICPs within the working area, directly access the attribute information and location guidance for each ICP, and rapidly identify suitable points for marking. This improves the efficiency of control-point marking in photogrammetric workflows. In practice, control-point marking efficiency increased by about 40% compared with conventional manual operations.



```
pt_id: 35
ref_2: <memory at 0x000002640172DF00>
cgcs2000_x: [redacted]
cgcs2000_y: [redacted]
sh2000_x: [redacted]
sh2000_y: [redacted]
geom: 0101000020B0110000E9263188799815414E6210F843BA4A41
point_class: 屋脊角点
point_class_code: 2
keep_suggestion: 保留
keep_suggestion_code: 1
elevation: 8.533
date_collect: 2025-01-01
date_edit: 2025-08-29
geom_sh: None
personel_edit: [redacted]
pt_name_ori: 2025-170423
pt_name: 170423
pt_name_2: A
direction: 西北
direction_code: 4
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```

Figure 5. Interface of the control point information browsing tool

5.2.2 ISD During the construction of the ISD, existing vector datasets were utilized to accelerate sample production. To further improve efficiency, a sample inspection and quality control application was developed to replace traditional topological editing workflows. The system has two modes: a normal mode for routine interpretation and a change-detection mode for time-series analysis.

In this application, operators can sequentially browse sample images and their corresponding vector labels, with lightweight editing functions such as deleting polygons or modifying class names. Batch editing operations are also supported for multiple polygons. Only samples that pass visual and attribute inspection are retained in the final database, ensuring both production efficiency and sample reliability.

The ISD management system provides an integrated operational framework for efficient sample management and long-term maintenance(Figure 7). It comprises seven functional modules, including data import, data export, statistical analysis, data visualization, spatial query, attribute query, and data backup and recovery. Together, these modules support a standardized workflow covering data ingestion, verification, retrieval, visualization, and preservation, thereby ensuring that the database remains accurate, accessible, and scalable.

The ISD stores more than 300,000 image-label pairs, with the total data volume reaching the TB scale. To accommodate this larger and more heterogeneous data structure, MongoDB is adopted for sample storage and retrieval. Its document-oriented architecture is well suited to large-scale image sample organization, enabling efficient metadata indexing, flexible query execution, and high-throughput batch export. This design ensures that the ISD management system maintains good responsiveness and scalability under intensive urban interpretation tasks.

Cleaned sample data are imported by category with complete metadata, while queried results can be exported in multiple formats for model training. The system supports both attribute-based and spatial searches, enabling users to filter data by parameters such as sensor type, acquisition time, or coordinate extent. Statistical and visualization tools provide charts and

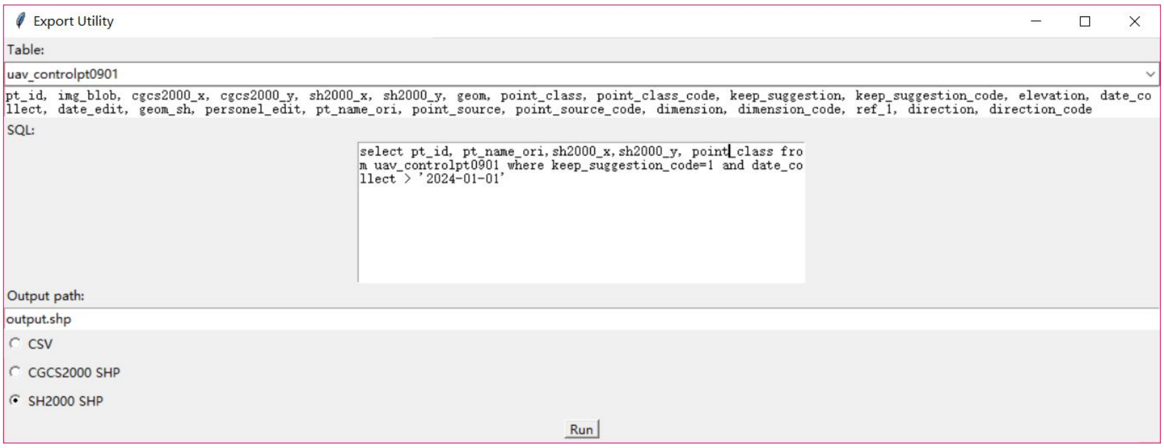

Table:

uav_controlpt0901

```
pt_id, img_blob, cgcs2000_x, cgcs2000_y, sh2000_x, sh2000_y, geom, point_class, point_class_code, keep_suggestion, keep_suggestion_code, elevation, date_co
llect, date_edit, geom_sh, personel_edit, pt_name_ori, point_source, point_source_code, dimension, dimension_code, ref_1, direction, direction_code
```

SQL:

```
select pt_id, pt_name_ori,sh2000_x,sh2000_y, point_class fro
m uav_controlpt0901 where keep_suggestion_code=1 and date_co
llect > '2024-01-01'
```

Output path:

output.shp

○ CSV
○ CGCS2000 SHP
● SH2000 SHP

Figure 6. Interface of SQL export tool

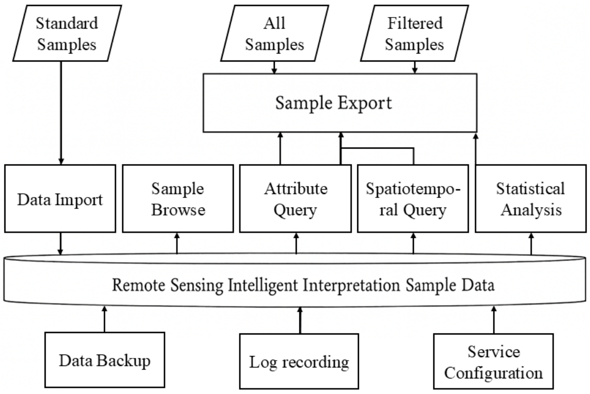

Figure 7. Structure of the ISD management system

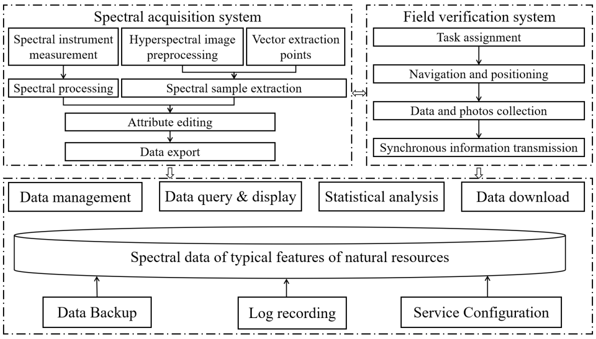

Figure 8. Overall functional structure of the SID

map-based interfaces for intuitive exploration, and a built-in backup mechanism ensures data integrity through full or incremental recovery operations.

5.2.3 SID To meet the needs of knowledge-based, quantitative, and application-oriented spectral data management, the Spectral Information Database is designed with three core components: a Spectral Data Acquisition System, a Field Verification Management System, and a Spectral Database Management System, as illustrated in Figure 8. Taking hyperspectral remote sensing imagery, ground-measured spectra, and prior knowledge as inputs, the system enables the acquisition, processing, and management of representative surface feature spectra and their associated environmental parameters.

Through the Spectral Data Acquisition System, operators can manage both ground-measured spectra collected by spectrometers and pixel spectra extracted from imagery. By leveraging existing vector data, pure pixel locations can be batch-extracted and superimposed on hyperspectral imagery to efficiently collect spectral samples. The attribute editing function allows detailed annotation of spectral metadata, including acquisition time, geographic location, meteorological parameters, and land cover types.

The Field Verification Management System utilizes data integration and sharing technologies to support functions such as verification task management, location navigation, data and photo acquisition, and cloud-based information synchronization, thereby improving the efficiency of field verification and data organization. For spectral sample points requiring on-site verification, operators can navigate to the designated location, photograph the target, record land cover attributes via mobile devices, and synchronize the information to the platform in real time.

As the core component, the Spectral Information Database Management System organizes and manages multi-type data, including images, spectra, and photographs. Users can query spectral data based on parameters such as land cover type, acquisition time, and geographic region. The statistical analysis module supports first-derivative, envelope, and other processing of spectral data, providing visualization for analytical interpretation. Additionally, data backup, user management, and service configuration modules ensure standardized management and data security.

6. Discussion and Future Work

6.1 Discussion

The construction of the three databases: ICPD, ISD, and SID, demonstrates a feasible pathway toward standardized, reusable, and intelligent remote sensing data infrastructure for megacity management. Compared with traditional project-based workflows, the database-driven approach enables the accumulation and re-use of geometric, semantic, and spectral information, greatly improving efficiency and consistency in large-scale image production.

From a technical perspective, the ICPD provides a reliable spatial reference by ensuring geometric alignment across multi-source and multi-temporal imagery. The ISD converts scattered monitoring results into structured, high-quality samples for model training and validation in monitoring tasks. The SID continues this process by linking imagery with physically meaningful spectral characteristics, thereby connecting qualitative interpretation with quantitative environmental assessment.

More importantly, the three databases form an interdependent system: geometric precision from the ICPD guarantees the spatial correctness of ISD samples and SID spectra; semantic information from the ISD supports intelligent spectral feature extraction; and spectral patterns from the SID validate and refine ISD classifications. This mutual reinforcement forms a continuous loop of data production, verification, and application, transforming traditional remote sensing workflows into a scalable and intelligent information production chain.

At the city-scale, such integration enhances the timeliness, interoperability, and interpretability of remote sensing products, supporting a wide range of applications from urban planning and resource monitoring to ecological evaluation and emergency response. The current implementation in Shanghai verifies the practicality of this architecture and highlights its potential for generalization to other metropolitan regions under unified technical standards.

6.2 Future Work

6.2.1 ICPD: Intelligent Control Point Management By integrating aerial triangulation and bundle adjustment workflows, the system will automatically detect, validate, and refine control points from new multi-source imagery, enabling the control point database to evolve dynamically with minimal manual intervention. During photogrammetric production, processes such as block triangulation, and sensor model optimization will be configured to automatically retrieve and apply suitable control points from the ICPD based on spatial extent and quality criteria. This tight coupling between the database and production workflows will reduce manual point selection, improve geometric consistency across projects, and ensure that all derived ortho-products and oblique models remain spatially unified over time.

6.2.2 ISD: City-Aware Intelligent Interpretation For the interpretation sample database, future work will explore the deployment of localized models tailored to specific urban contexts. These models will be trained on the localized ISD samples, enabling them to understand and respond to the actual analytical needs of city management—such as illegal construction monitoring, land-use transformation, or urban greening evaluation. With continual fine-tuning, the system could achieve adaptive interpretation that aligns with evolving urban policies and data characteristics.

Moreover, since the datasets in the ISD are spatially coordinate-aligned, additional data sources such as DSM, DEM, SAR imagery, and point clouds can be efficiently incorporated into the framework. The existing labels can be projected onto these datasets and reused with only minor correction, which substantially lowers the workload of multi-source annotation. This capability will facilitate the construction of richer training samples and support the development of city-aware interpretation models with stronger cross-source generalization and fusion capability.

6.2.3 SID: Ecological and Environmental Intelligence The spectral information database will be extended toward ecological monitoring and quantitative environmental assessment. By coupling spectral indices with physical and biochemical parameters, the SID will support fine-scale estimation of vegetation health, water quality, and soil properties. A particular emphasis will be placed on Green–Blue space analysis, integrating spectral and spatial indicators to monitor vegetation–water interactions, ecosystem resilience, and the effectiveness of urban ecological restoration projects.

Furthermore, the spatial scope of the SID will be extended to the Yangtze River Delta region. Such an expansion is important because natural features and ecological processes are not bounded by administrative borders. For instance, the ecological analysis of water systems requires complete watershed-scale observations rather than data confined to a single city. Regional-scale database construction will therefore provide a more coherent foundation for cross-boundary ecological assessment and support integrated environmental management in the broader metropolitan region.

Together, these directions point toward an intelligent, adaptive, and interoperable remote sensing infrastructure capable of supporting sustainable management and analysis in megacities and beyond.

7. Conclusion

We presented an integrated framework connecting Control Point Database, Interpretation Sample Database, and Spectral Database to support megacity management. By aligning geometry, semantics, and physics, the system builds a workflow from raw multi-source imagery to ARD, substantially improving automation, efficiency, and intelligence. The Shanghai case study demonstrates concrete gains and validates the practicality of the approach.

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