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Towards a Unified Identifier of Satellite Remote Sensing Images

Jiahe Wang [1,2], Jin Wu [1,2,*], Mingbo Wu [1,2], Yuxiang Lu [3], Shangwen Lu [3], Dayong Zhu [3] and Chenghu Zhou [1,2]

[1] State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; wangjiahe0011@igsnrr.ac.cn (J.W.); wumingbo14@mails.ucas.ac.cn (M.W.); zhouch@lreis.ac.cn (C.Z.)
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] Digitwinology International (Kunshan) Information Technology Co., Ltd., Suzhou 215300, China; luyuxiang21@mails.ucas.ac.cn (Y.L.); lu.shangwen@ddeworld.org (S.L.); zhu.dayong@ddeworld.org (D.Z.)
* Correspondence: wuj.17b@igsnrr.ac.cn

Abstract: The rapid growth of Earth observation technologies has resulted in over 2000 operational remote sensing satellites, collectively generating an exabyte-scale volume of data. However, despite the availability of large data-sharing platforms, global remote sensing imagery still faces challenges in seamless access, precise querying, and efficient retrieval. To address these limitations, this study introduces the concept of the "Digital Imagery Object" (DIO) and develops a unified identification framework for satellite remote sensing imagery. The proposed approach establishes a structured identification and parsing system based on core metadata, including data acquisition platforms and imaging timestamps. This enhances the consistency and standardization of multisource imagery encoding, enabling unified identification and interpretation under a common set of rules. The system's feasibility and effectiveness were demonstrated through the integration and management of diverse global datasets, highlighting its ability to streamline multisource data workflows. By supporting standardized management and one-click parsing, this framework facilitates efficient imagery sharing and lays the foundation for its use as a tradable digital resource on the internet. The study offers a practical solution for addressing current challenges in remote sensing imagery management, paving the way for improved accessibility and interoperability of Earth observation data.

Keywords: remote sensing imagery; unified identifier; geographic information system; object-oriented

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1. Introduction

Since the launch of the first remote sensing satellite in the 1960s, the number of operational remote sensing satellites has exceeded 2000 globally, with the total volume of data reaching the exabyte (EB) scale [1–3]. Particularly in the era of high-resolution satellites, the volume of remote sensing data has grown exponentially, significantly enhancing data acquisition capabilities and driving the development of data-sharing services. The scientific and applied communities place great emphasis on the sharing of remote sensing data. For instance, the United States Geological Survey (USGS) has established the Earth Explorer platform, providing long-term Landsat imagery, hyperspectral data, and reconnaissance satellite data. Additionally, platforms such as NASA Earthdata Search, NOAA Data Access Viewer, and ESA WorldCover offer free Earth observation data for global users.

Although these official platforms promote data utilization by integrating and standardizing remote sensing imagery, the development of internet and cloud computing technologies has led to the emergence of numerous platforms that store and integrate remote sensing imagery for their own purposes. The lack of unified standards has exacerbated issues such as data fragmentation, inconsistent formats, and "data silos" [4]. Meanwhile, cloud computing providers like Alibaba Cloud, Amazon Web Services (AWS), and Microsoft store vast amounts of remote sensing imagery on their platforms to meet diverse user needs. The STAC (Spatio-Temporal Asset Catalog) protocol addresses these challenges by defining unified metadata structures and standardized interfaces, enabling the integration and standardized management of multisource remote sensing data [5]. However, due to significant differences in design philosophies, objectives, functional structures, and implementation technologies among various platforms, the issue of data silos has become increasingly severe. This has hindered the sharing, circulation, and utilization of scientific data. Consequently, given the valuable and massive resources of remote sensing imagery, addressing core challenges, such as achieving specialized storage, intelligent management, and one-stop automated access to global remote sensing imagery, has become a pressing issue in the field of remote sensing [6].

Extensive practical experience in Information-Centric Networking (ICN) has shown that identity identification is the foundational component for enabling rapid access and seamless retrieval of global digital resources [7]. Key functionalities, such as resource discovery, governance, analysis, and circulation, depend on identity services. For example, all cloud services in AWS rely on Amazon Resource Names (ARNs) for identity management.

From an informational perspective, remote sensing imagery is a type of digital resource. Identity identification consists of two main components: a unified abstract model of digital resources and their standardized encoding and resolution. Regarding abstraction, satellite remote sensing imagery can be represented at two levels: individual image scenes and datasets comprising groups of images. Current platforms mainly organize and manage imagery at the dataset level. For instance, NASA Common Metadata Repository (CMR) defines two global abstract models: Granules (individual scenes) and Collections (groups of related scenes) [8]. Similarly, the STAC standard, widely adopted by platforms like Earth on AWS [9], Google Earth Engine [10], and Planetary Computer [11], abstracts imagery into Items and Collections. However, these standards prioritize Collections as "first-class citizens", resulting in inconsistent priorities between individual images and their relationships. This hampers image-level data visibility (findability) and accessibility, as search paradigms are largely collection-centric.

For encoding and resolution, global remote sensing imagery lacks consistent encoding rules, and its predictability during resolution is poor [12,13]. Many providers adopt complex structured encoding schemes, often composed of multiple fixed-length segments corresponding to metadata elements [14,15]. For example, Landsat imagery identifiers include satellite ID, processing level, acquisition date, and tile number, ensuring internal uniqueness [16]. However, the inconsistent rules and diverse metadata across providers make integrating multisource data challenging, reducing readability and suitability for standardized identity services. Additionally, resolution predictability is unreliable; some identifiers do not support resolution, while others may return image entities, metadata, or even login pages, lacking a unified framework for accessing satellite imagery [17].

To address these challenges in global remote sensing imagery access and management, this paper proposes treating individual satellite remote sensing images as "digital image objects" (DIOs), defined as first-class entities that are directly accessible and operable on the internet. Based on DIOs' independence and resolvability, we designed a Digital Identity Identifier (DII) system, which includes a corresponding encoding and parsing system for DIOs. The DII structure for encoding DIOs is centered around the imaging acquisition start time, emphasizing the expression of space through time. Specifically, as a result of satellite observations, the spatial position corresponding to a remote sensing satellite at a given moment is fixed. This system enables one-click access and standardized management of multisource heterogeneous imagery, effectively promoting the sharing of remote sensing data and contributing to addressing the issue of "data silos".

2. Digital Image Object

2.1. The Essence of Satellite Remote Sensing Imagery

Satellite remote sensing imagery, referred to as "remote sensing imagery", generally refers to signals captured by sensor systems onboard satellites that record the interaction between electromagnetic energy (e.g., light, heat, and microwaves) and matter, either in analog or digital form. After the raw data are processed and released, they result in remote sensing images and associated datasets [18,19]. Satellite remote sensing imagery can be categorized into two types: imaging and non-imaging. This study focuses on imaging-based satellite remote sensing imagery.

A single scene of remote sensing imagery encompasses not only the image file itself, but also associated metadata files. These metadata files describe information such as the geographic coordinates, sensor characteristics, acquisition time, and spatial resolution. Therefore, a single scene of remote sensing imagery is not a standalone file, but rather a collection of multiple components. Among these, the image file serves as the core data, while the metadata files provide precise interpretation and usage instructions for the imagery.

Viewing these files as a cohesive unit facilitates a comprehensive understanding and utilization of the spatial information and attribute features contained in the imagery. During storage and management, treating a single scene of remote sensing imagery as a combination of multiple interrelated files is critical. This combination reflects not only the connections between the image file and its metadata files, but also their underlying semantic structure: the imagery data represent the physical world, while the metadata files assign spatial positions and other essential semantic information to the imagery data. This integration of data and metadata ensures the interpretability and operability of remote sensing imagery, ultimately enhancing its value for subsequent applications.

2.2. The Concept of Digital Image Object

In the process of establishing a unified identification system for remote sensing imagery, it is essential to first conduct a systematic abstraction of all imagery. Based on the object-oriented abstraction concept, this study considers a single scene of remote sensing imagery as an operable and describable digital image object (DIO), treating it as a first-order data entity [20].

A first-order data entity indicates that the digital image object exists independently and in a complete form, and it can be directly accessed and operated. Here, "first-order" means that users can directly access the data through identification and resolution without relying on indirect methods, such as API calls. "Entity" signifies the independence of the digital image object, highlighting that the remote sensing imagery object exists as an independent and complete entity without being dependent on any other entity.

This study posits that remote sensing imagery is not merely a collection of data files, but rather an object with specific attributes and behaviors (Figure 1). The object-oriented approach is first reflected in the classification and grading of imagery. Classification refers to systematically categorizing remote sensing imagery based on standards such as satellite acquisition platforms and sensor types, while grading involves further refinement based on criteria such as product types and processing levels. Through classification and grading, remote sensing imagery data from diverse global sources can be clearly organized and differentiated, ensuring accurate identification and encoding under a unified framework.

This lays the foundation for subsequent processes, such as coding, management, one-stop indexing, and applications.

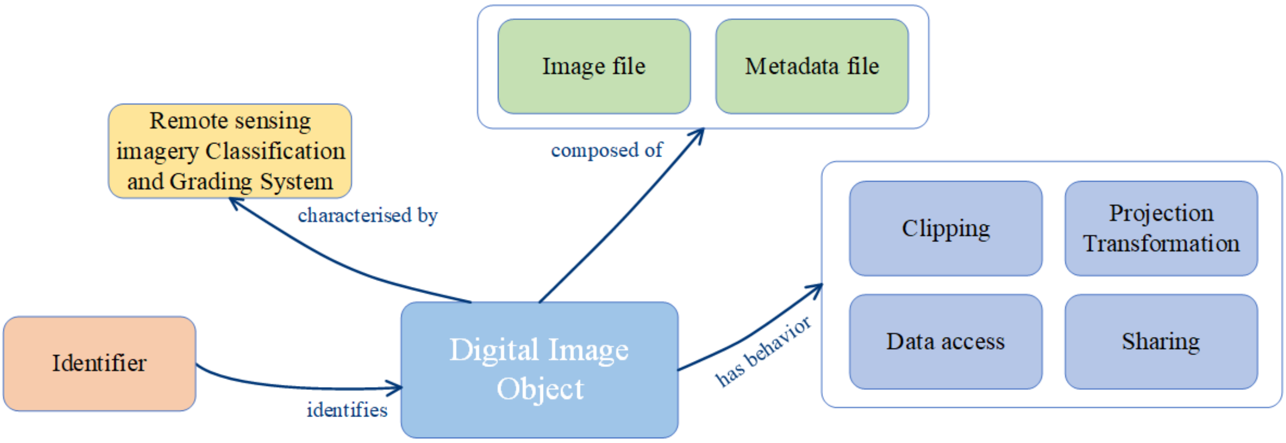

Figure 1. The essence of the digital image object.

Encoding is one of the core elements of a digital image object. As a type of digital object on the internet, a unique identifier for remote sensing imagery plays a critical role in its resolution, operation, and management. Each single scene of imagery requires a unique identifier (ID) and the formulation of reasonable encoding rules. These rules should comprehensively consider the intrinsic properties of remote sensing imagery, as well as its classification and grading system, ensuring that multisource digital image objects have unique identifiers within a unified framework. This provides the basis for imagery data transactions and sharing as well as a standardized guarantee for its reliable resolution in the digital domain.

Another important characteristic of a digital image object is its dynamic behavior. From an object-oriented perspective, a digital image object encompasses not only static attributes, such as geographic coordinates, resolution, and sensor types, but also operational behaviors. These behaviors include actions such as clipping, projection transformation, resampling, etc. With the growing importance of digital resources, particularly in scenarios involving resource transactions and sharing, data access and sharing, the operational behaviors of digital image objects must be integrated into the object definition. This allows users to flexibly handle various tasks while maintaining the core attributes of the imagery. By encapsulating these operations, digital image objects can support the integration and analytical processing of various application scenarios.

Through this object-oriented processing approach, a single scene of remote sensing imagery transforms from being merely a collection of data files into a digital image object with attributes and behaviors. The object-oriented description provides technical support for the sharing, transaction, access, and application of imagery data, promoting the utilization and value extraction of remote sensing imagery in various fields.

3. Principles and Framework of Digital Image Object Identity Identification

3.1. Principles of Digital Image Object Identity Identification

As a digital resource, a digital image object (DIO) needs to be assigned an effective identity identifier based on a unified encoding system to facilitate its access and retrieval. Currently, there are various identity identification systems for digital resources, such as the Digital Object Identifier (DOI), W3C Distributed Identifier (DID), and PIDs, used by the DeSCI organization for scientific resources. In the field of remote sensing, image suppliers have also developed their own encoding rules based on the characteristics of the images. Based on the above identity identification research, this study has established seven fundamental principles for the digital image identifier (DII) [21–27]:

1. Global Uniqueness. Each DIO corresponds uniquely to a DII, and different DIOs are assigned different DIIs. Currently, due to the widespread use of remote sensing imagery, the same scene data may have multiple versions produced by different institutions, each assigned a different encoding name. This situation leads to a lack of uniformity and standardization in image identification across platforms and suppliers. The core of the DII is to assign a unique identity to the DIO rather than merely a coding name. This identity can precisely map to a specific image object, ensuring its recognition and resolution capabilities on a global scale.
2. Scalability. With advancements in remote sensing technology and the expansion of application scenarios, the number of remote sensing image data products continues to increase. This requires the DII to have good scalability so that newly added data can be smoothly incorporated without affecting existing identifiers.
3. Persistence. Once a DII is assigned to a DIO, it remains valid permanently, and does not change with any alterations to the object or changes in management responsibilities. Remote sensing data often involve long time cycles, so ensuring the persistence of the identifier is crucial. This can effectively maintain the validity of older data, preventing access difficulties caused by identifier expiration or data loss, and ensuring the continuous availability and integrity of data.
4. Normativity. The composition structure of the DII should be clear, and the coding rules should be simple to ensure consistency across multisource, heterogeneous satellite remote sensing imagery.
5. Resolvable. In this study, DIOs are considered first-order data entities. The goal is to simplify the process for users to access image data, enabling direct resolution from the DII to the DIO.
6. Interpretability. Each character in the DII should have clear semantics, enabling users to understand and identify the basic information of the DIO. By integrating key metadata into the DII, users can intuitively learn about the basic information and related attributes of the DIO, thereby reducing the need for additional metadata retrieval. Furthermore, the clear semantic structure supports automated data processing and analysis, improving the overall efficiency of data management.
7. Compatibility. Due to the global nature of remote sensing imagery, the DII must be designed to ensure compatibility, enabling it to serve as a unique identifier for global DIOs. It must also be compatible with existing image encoding systems, allowing for interconversion. By interfacing with current image encoding systems, the DII can support cross-platform data exchange and usage, enhancing the interoperability of data and the flexibility of systems. This compatibility provides an efficient way to manage and retrieve data and enables smoother integration and utilization of data across different systems and platforms.

3.2. The Unified Identity Identification Method for DIO

3.2.1. Design of the Identity Structure for DIO

Designing a reasonable structure for the DII is critical to ensuring unified management and efficient utilization of data identity. The traditional naming process for remote sensing imagery typically combines multiple meaningful components to form a holistic identifier, a convention widely adopted in the remote sensing field. Building on this characteristic, the proposed DII aims to provide a unified, concise, and efficient identification scheme for DOIs globally. This study, grounded in the essence of remote sensing imagery and inspired by classification and hierarchical principles, develops an identifier structure that facilitates data sharing and efficient management.

First, the initial component of the DII structure encodes the observation type of the DIO. Referencing the Earth observation standards established by the Open Geospatial Consortium (OGC), remote sensing imagery is categorized into six major types: optical imagery (OPT), radar imagery (SAR), atmospheric observation products (ATM), altimetry data (ALT), limb observation imagery (LMB), and synthetic and systematized products (SSP) [28]. These categories encompass diverse observation modalities, from visible light to radar, reflecting the variety and broad applications of remote sensing data. To ensure consistency and standardization, the DII structure must explicitly indicate the observation type, maintaining a unified classification standard across different platforms for processing and application.

Second, the core descriptive elements of the DII structure capture three key characteristics of the DIO. Satellite remote sensing imagery is generated based on the imaging principles of satellites capturing specific areas at specific time points or intervals. Satellites, equipped with sensors, continuously capture imagery data as they orbit, with acquisition times precise to the second, ensuring temporal accuracy. Therefore, satellite platform, sensor, and data acquisition time are essential features of satellite remote sensing imagery [29]. Note that for a given satellite platform, its spatial position at a specific acquisition time is fixed. For instance, geostationary satellites continuously observe the same area from a fixed position, while polar-orbiting satellites traverse different Earth regions at regular intervals. This study standardizes the use of acquisition start time in the identifier to represent the temporal aspect of data acquisition. By combining satellite platform, sensor, and acquisition start time, the spatial position of the satellite and the spatial extent of the remote sensing data can be implicitly identified. This approach simplifies necessary information and focuses on the core characteristic of satellite imaging time, enhancing identifier accuracy and consistency.

Finally, when designing the DII structure, the integration of product name, product tag, and processing level was incorporated to achieve unified identification for various types of satellite remote sensing data products. From the perspective of imaging principles, remote sensing products can be categorized into original image products, which adhere to imaging principles, and derivative products, which do not conform to these principles. Original image products are typically organized and published by satellite providers in units of scenes based on the temporal and spatial sequences of satellite acquisitions. After acquisition, these data usually undergo geometric correction, atmospheric correction, and other processes to produce remote sensing products with different processing levels, which are then made available to users [30]. The processing level provides users with explicit information about the processing steps that each data product has undergone during its production. In contrast, derivative products are generated from original image products through additional processing. For example, analysis ready data (ARD) is produced by clipping according to specific grid divisions and annotating interfering factors such as clouds, making it more readily applicable in broader use cases compared to original imagery [31,32].

In summary, this study designs the DII structure by combining the observation type (T), metadata (M), and processing information (P) through a function (f), forming a complete identification code. The definition is as follows:

$$\begin{cases} DII := f(T;(M,P)) \\ M = (S, R, T_s) \\ P = \left(N, T_p, L\right) \end{cases} \quad (1)$$

Specifically, the function $f()$ is a mapping process that integrates the three elements to generate a globally unique and interpretable identifier for DIOs. T represents the observation type of the remote sensing imagery, such as optical imagery (OPT) or radar imagery (SAR). This part of the code ensures that different types of imagery can be explicitly distinguished within the identification system. For example, an optical image from the Landsat satellite would have T = OPT, while a radar image from Sentinel-1 would have T = SAR.

The imagery metadata (M) consists of three key attributes: S, which denotes the satellite platform and identifies the satellite that acquired the imagery; R, representing the sensor type, which describes the sensor model that generated the imagery; and T_s, the data acquisition start time, indicating the exact moment when the imagery acquisition began. The imagery processing information (P) includes three components: N, the product name, which identifies the processed product derived from the imagery; T_p, the product tag, which distinguishes between original imagery products and derivative products; and L, the processing level, which specifies the processing stage of the imagery.

3.2.2. Design of Digital Image Object Identification Rules

When designing the encoding rules for the DII, it is essential to ensure that each component has a clear and standardized encoding method to achieve consistency and readability across different platforms and applications. To this end, this study proposes specific encoding schemes for each component based on the previously defined structure, ensuring the global applicability and efficiency of the DII.

Figure 2 shows the sequence of DII components, indicating that the entire DII encoding structure must follow this specific sequence to maintain consistency and logical coherence. The first part of the encoding is the observation type (Type), which is also the T in Equation (1). It represents the primary observation mode of the remote sensing imagery, such as optical or radar imagery. This is followed by the satellite platform (Satellite) and sensor type (Sensor), which respectively identify the specific satellite capturing the image and the onboard sensor used. These correspond to S and R in Equation (1).

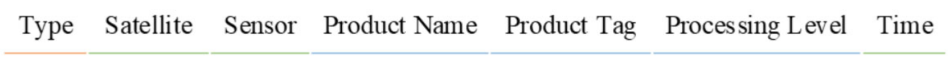

Figure 2. The sequence of DII.

Next, the product name (Product Name) and product tag (Product Tag) further refine the classification of the imagery product and describe its content characteristics. These elements, which correspond to N and T_p in Equation (1), respectively, enable users to quickly determine the purpose and application scenarios of the data. For original imagery products, the product tag is represented as "__". For derivative products, the tag provides sequential encoding for multiple imagery slices acquired at the same timestamp. The processing level (Processing Level) distinguishes between different stages of data processing, helping users to understand the extent of data refinement, corresponding to L in Equation (1).

Finally, the data acquisition start time (Time) encoding is positioned at the end of the identifier. Since the acquisition time is unique for each digital image object, this component ensures the uniqueness of each DII, corresponding to T_s in Equation (1).

To enhance the readability of the DII, this study divides it into four main parts, separated by underscores ("_"). Each character in the DII can be a letter or a digit, and the length of each part is not fixed. Figure 3 shows the corresponding DII, which is derived from an example of Landsat 8 imagery to illustrate the encoding rules. Specifically, this DII is constructed based on the Landsat 8 imagery file "LC08_L2SP_025029_20240924_20240925_02_T1", with further explanations of each component of the DII structure provided below.

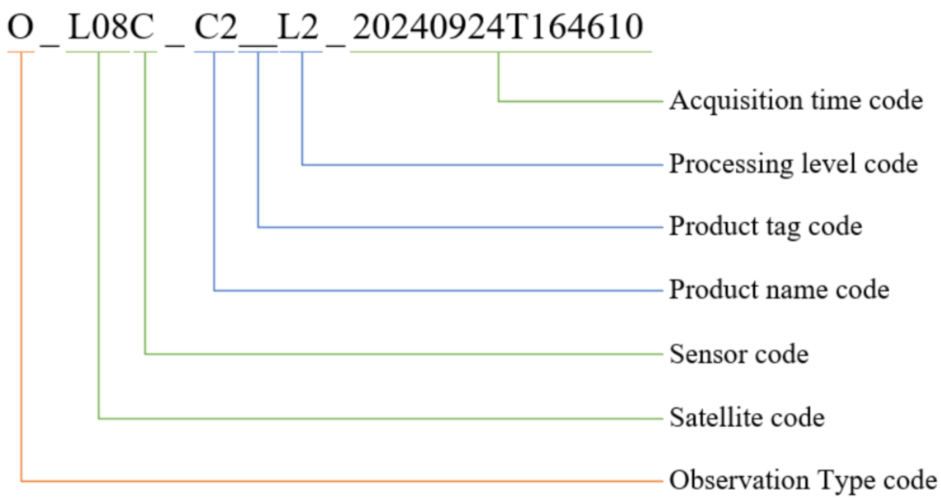

Figure 3. An example of the DII representation.

First, the observation type code (Type) is "O", abbreviated from "OPT" for optical imagery. Next, the satellite platform and sensor codes (Satellite & Sensor) are represented as "LO8C", where "L08" denotes the Landsat 8 satellite platform and "C" indicates that this digital imagery object was acquired by the OLI and TIRS sensors.

Then, the product name, product tag, and processing level are encoded as "C2__L2", indicating that the data product belongs to Collection 2, is an original imagery product (represented by the '__' separator), and has a processing level of Level 2. Finally, the data acquisition time code (Time) records the start time of this imagery acquisition, which is 24 September 2024, at 16:46:10, derived from the metadata file. This start time, recorded as the scene acquisition time by the satellite platform, is converted to Coordinated Universal Time (UTC), with "T" used as a separator.

In summary, for any digital imagery object, its unique DII can be generated by retrieving the corresponding information from the metadata file and encoding it according to the DII structure.

3.3. Digital Image Object Identity Identification Framework

This study proposes a framework for DIOs and introduces a method called "name2DII" for the unified identification of DIOs. The method takes the name of the image object as input and outputs a DII identity in string format, ensuring the uniqueness and standardization of the image object.

Figure 4 illustrates the overall organizational structure of DIOs. In this framework, Satellite Image and ARD Image are subclasses of DIO, alongside other types of image products (Other Image Products). The framework is based on object-oriented principles, emphasizing the inheritance and extensibility of image objects. Whether it is raw satellite images (Satellite Image) or analysis-ready data (ARD Image) that have undergone standardized preprocessing, both are considered instances of DIO, sharing common attributes and behaviors. For example, each image object must have a unique name (Name), which can be processed by the "name2DII" method to convert it into a standardized DII identifier.

The core functionality of the name2DII method is to parse the image object name, extract key metadata (such as satellite platform, sensor type, acquisition time, processing level, etc.), and generate a globally unique identity according to the DII encoding rules. Specifically, the method is designed to be compatible with various types of image products, whether they are scene-based raw images or derived products, such as ARD data. Additionally, the framework is designed with scalability in mind, ensuring that it can adapt to the diversification of image product types in the future.

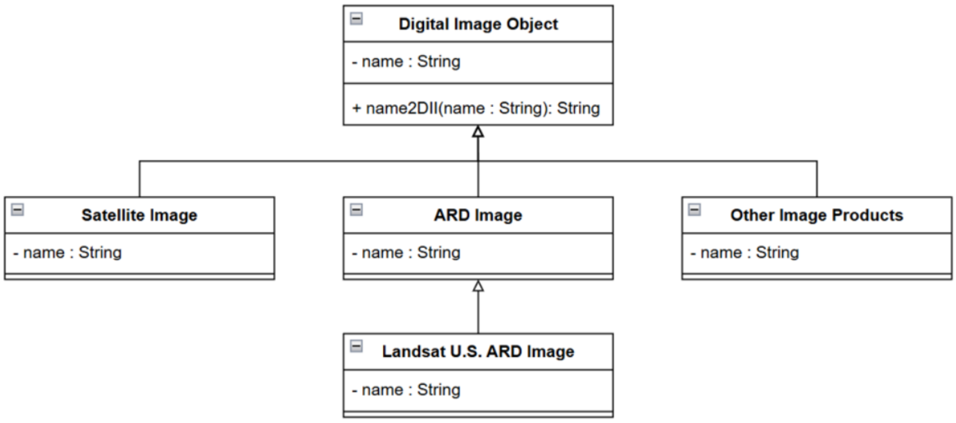

Figure 4. The overall organizational structure of DIOs.

4. Digital Image Object Identification System

4.1. Design of the Identification System

This study implements and integrates the digital image identification method into the Digital Image Identification System platform, aiming to provide users with a one-stop solution for accessing and sharing remote sensing images conveniently. The platform is designed based on user needs, combining a streamlined user interface with efficient image processing workflows to enable users to easily obtain the desired image data (Figure 5).

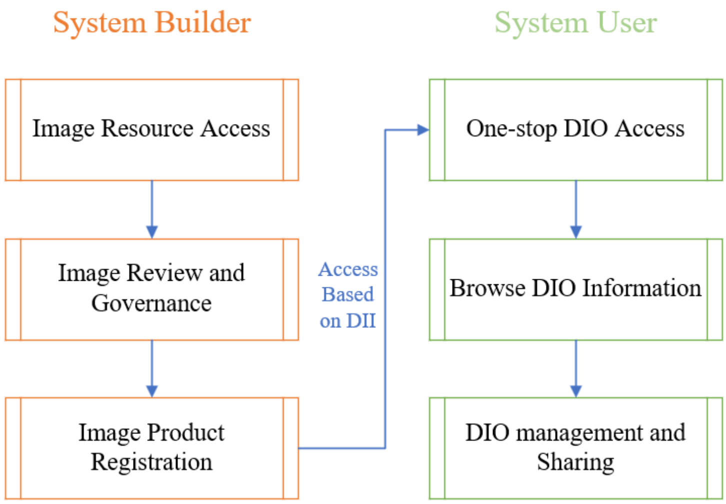

Figure 5. Platform functional modules and user interaction workflow.

During the platform development, the builders integrated image resources through internet technologies and conducted rigorous auditing and management of these images, establishing an image registration system. Each scene image is assigned a unique DII upon registration to ensure orderly organization and accurate retrieval of image resources. The introduction of DII provides a stable foundation for accessing and parsing image resources on the platform while offering users an effective means of image retrieval. Users can directly locate target images using DII, enabling image access and information browsing, thereby improving workflow efficiency. Through this DII-based one-stop access method, users can quickly and conveniently retrieve and access the required image data, simplifying the processes of image acquisition and sharing while enhancing usability and efficiency.

4.2. Case Study

An identity system is essential not only for the registration and identity confirmation of digital image objects, but also as a foundational component to enable users to conveniently access and operate these objects. This study classifies image products into original image products and derivative products with distinct approaches for generating their corresponding digital image identifiers (DIIs).

For original image products, extensive research and validation conducted in this study confirm that the DII corresponding to such DIOs can be effectively extracted from either the product title or metadata. Specifically, in Section 3.2.2, the composition of the DII was detailed using a Landsat 8 scene as an example. In addition, the original image products analyzed in this study are summarized in Table 1. From this table, it is evident that the information needed for constructing the DII is a subset of the information found in the original product name, with the remaining necessary components available in the metadata. Therefore, the DII structure compatibility for identifying original image products has been validated through this process.

Table 1. Comparison of information in naming rules among major remote sensing imagery providers and DII.

		Landsat 8 & 9	MOD09	Sentinel-2A	Sentinel-3A	Sentinel-5P	Gaofen-1	Gaofen-5	Gaofen-7	DII
Temporal Information	Image Data Acquisition Start Time	●	●	●	●	●	●	●	●	◉
	Image Data Acquisition End Time				●	●				
	Data Processing Time	●	●		●	●				
Spatial Information	Tile Number		●	●	●					
	Absolute Orbit Number					●	●			
	Relative Orbit Number			●	●					
	Processing Baseline Number			●						
	Data Tile Number	●			●					
	Data Product Central Longitude						●	●		
	Data Product Central Latitude						●	●		
	Covered Geographic Location								●	
Product Information	Satellite/Mission Identifier	●	●	●	●	●	●	●	●	◉
	Processing Level	●	●	●	●	●	●	●		◉
	Sensor Identifier	●			●	●	●	●		◉
	Product Name		●		●	●	●	●	●	◉
	Resolution Type								●	
	Product Type				●					
	Product Serial Number			●			●	●		
	Dataset Name	●	●			●				◉
	Dataset Type	●								
	File Type	●								
	Observation Data Downlink Orbit Number							●		
	Product Tag									◉

Note: ● indicates information included in the naming rules of the respective remote sensing imagery provider. ◉ represents information included in the DII naming framework.

In contrast, derivative products follow the same DII structure, but the product tag component differs. Since various derivative products require specific identification strategies, this study uses analysis ready data (ARD)—a widely adopted example of derivative products—to illustrate the DII compatibility [31]. ARD undergoes a series of preprocessing steps, making it immediately ready for analysis, which significantly reduces the workload for users engaged in time-series studies.

For these secondary-processed datasets, the DII demonstrates strong compatibility by enabling a unified identity system. This study showcases the application of the DII to Landsat U.S. ARD data, integrating essential metadata into the DII structure and presenting a method for generating unique identifiers. Figure 4 illustrates the organizational structure of Landsat U.S. ARD data products within the ARD Image object. Using the "name2DII" method, unified identification is achieved within the digital image object (DIO) framework.

The Landsat U.S. ARD data products are part of the Landsat Collection 2 series and primarily cover the contiguous United States (CONUS), Alaska, and Hawaii. These regions are associated with specific tile systems, identified in the data naming conventions as "CU", "AK", and "HI" to denote the coverage areas. The image data for each region are divided based on a specific tiling system and are labeled with corresponding row and column numbers. These products encompass four primary data types: Top of Atmosphere (TOA) reflectance, Brightness Temperature (BT), Surface Reflectance (SR), and Surface Temperature (ST).

It is worth noting that Landsat U.S. ARD data exhibit the following two characteristics:

1. Irregular boundaries:

The spatial boundaries of ARD data are typically constrained by the boundaries of the scene-based satellite images. As shown in Figure 6, taking the ARD data "LC08_CU_002009_20220128_20220208_02" as an example, the coverage includes three scene-based satellite images: "LC08_L2SP_043033_20220128_20220204_02_T1", "LC08_L2SP_043034_20220128_20220204_02_T1", and "LC08_L2SP_043035_20220128_20220204_02_T1". These three extents have spatial ranges that differ from the tiling method of ARD data. As a result, the left boundary of the ARD data is influenced by the strip patterns of these extents, forming an irregular geometric shape.

2. Temporal identifier ambiguity:

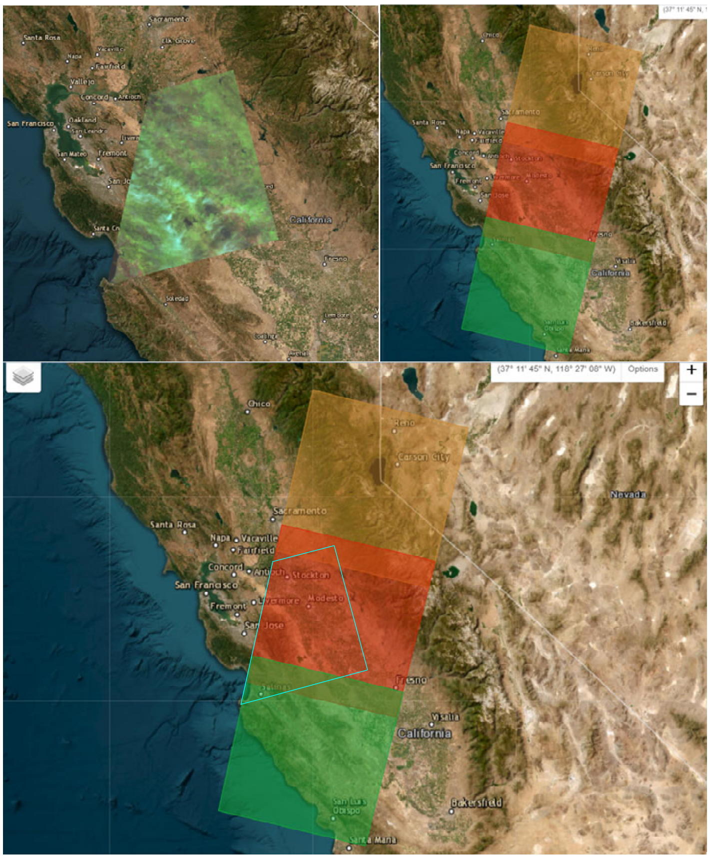

Figure 6. The ARD data (top left), three scene-based satellite image extents (top right), and their spatial relationship (bottom). The colors in the figure represent different image extents: green, red, and orange indicate the spatial extents of the three scene-based satellite images, while the blue boundary outlines the extent of ARD data.

Since ARD data are generated through the resampling and segmentation of multiple scene-based images, the acquisition time of the data is usually the median acquisition time of all images within the range. For example, in the case illustrated in Figure 7, the generation time for multiple ARD tiles is uniformly labeled as "2024-07-13".

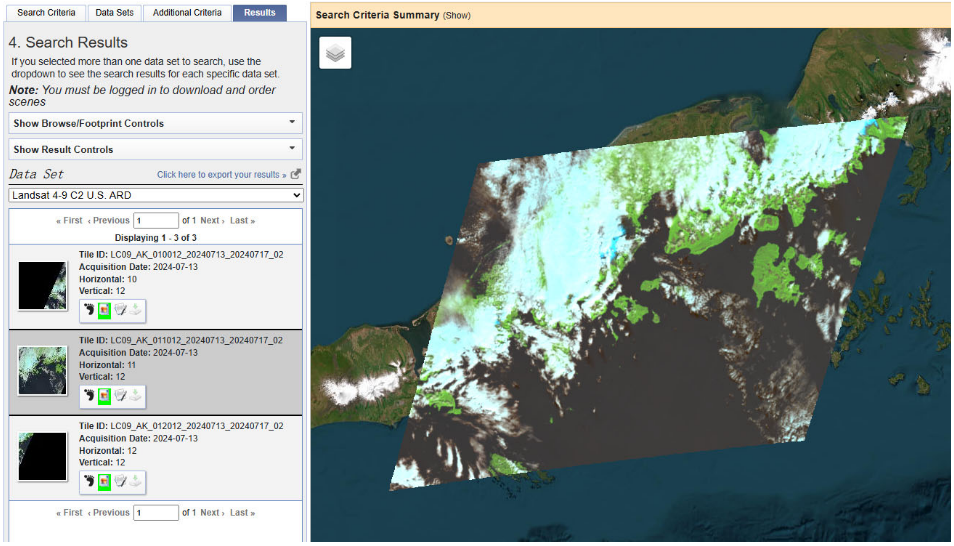

Figure 7. ARD data with the same datetime showing on EarthExplorer.

This study addresses the challenges posed by these characteristics by integrating key metadata (such as region, tile number, and acquisition time) into the DII encoding rules through the “name2DII” method. Additionally, it introduces the Product Tag as an auxiliary identifier to distinguish between multiple ARD data with the same acquisition time. This design ensures not only the uniformity and uniqueness of DII for both raw images and derived products, but also enhances its applicability to complex image products.

For the ARD data in this study, when multiple ARD data share the same acquisition time, a row-major order-based numbering system is employed to achieve unique identification. Specifically, the datasets are ordered row-by-row, column-by-column, and assigned incremental numbers starting from “01”. This approach replaces the expression of absolute spatial boundaries with relative spatial positions, avoiding duplicate identifiers and further improving DII adaptability to secondary processed imagery data.

In the implementation, this study designed and developed the “name2DII” algorithm-parsing workflow specifically for ARD data. The algorithm extracts the necessary information (e.g., acquisition time, region, and tile number) from the input image metadata and generates unique identifiers based on the DII encoding rules. During this process, the Product Tag serves as an auxiliary identifier to ensure the effective differentiation of multiple ARD data with the same acquisition time but differing spatial distributions.

Algorithm 1 visually illustrates the specific workflow for extracting key information from ARD data and generating DII. The process begins by parsing fundamental metadata from the input ARD data, including acquisition time, tile number, and region. For ARD data sharing the same acquisition time, a tile sorting rule based on relative spatial positions is applied, assigning unique numbers in row-major order. These numbers, which correspond to the ’product tag code’ in the DII structure, serve as the ’num’ element during the encoding process. Subsequently, the parsed time identifiers, region, product characteristics, and sorting numbers are combined to generate a complete identifier following the DII encoding rules. Finally, the resulting DII is output, ensuring its global uniqueness and consistent interpretability, thereby enabling precise identification and standardized management of ARD data.

Algorithm 1: "name2DII" algorithm for ARD data.

```
Input: ARDImageDataRecords
Output: DII
Function name2DII4ARD(ARDImageDataRecords):
    foreach record in ARDImageDataRecords do
        Extract 'satellite name', 'satellite number', 'USArrange', 'hor', 'ver'
         information;
        Trim 'datetime' to seconds level;
    end
    create 'num';
    foreach unique 'datetime' in record do
        if Count(record with same 'datetime') is more than 1 then
            order with 'hor' and 'ver' and number from '01' and keep plus one to
             fill in 'num';
        else
            set 'num' to '00';
        end
    end
    Complete other information according to DII structure;
```

Using the three ARD data shown in Figure 7 as an example, the above method was applied to parse and encode them, generating the corresponding DII identifiers, which are shown in Figure 8. These identifiers fully reflect the encoding rules combining temporal identifiers, spatial positions, and product characteristics, successfully achieving unique identification for multiple ARD data with the same acquisition time but with different spatial distributions.

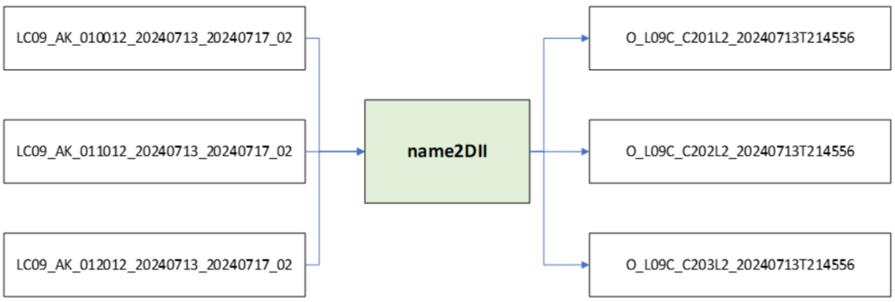

Figure 8. The DIIs corresponding to three ARD data with the same acquisition time.

This study registered over 2.1 million ARD data and successfully assigned a unique DII identifier to each. Figure 9 illustrates the interface of the identification system, which is divided into three sections: left, middle, and right. The left section is dedicated to the categorical management of digital image objects, displaying different types of image data in groups. The right section shows a list of specific image objects, each uniquely identified by its DII, enabling a quick search and precise data location. The middle section serves as a visualization area, providing an intuitive display of the spatial distribution of image objects and related information. During system operations, users can perform various actions on image objects through their DIIs, such as loading images, browsing attribute information, or conducting further analyses, thereby achieving efficient data management and utilization. Figure 10 shows the interface displaying a DIO.

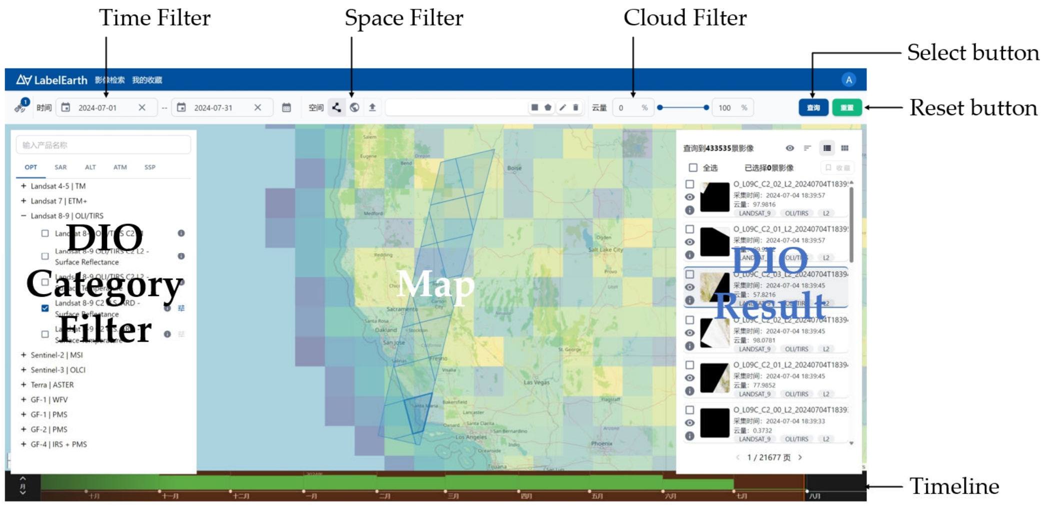

Figure 9. The interface of the identity identification system.

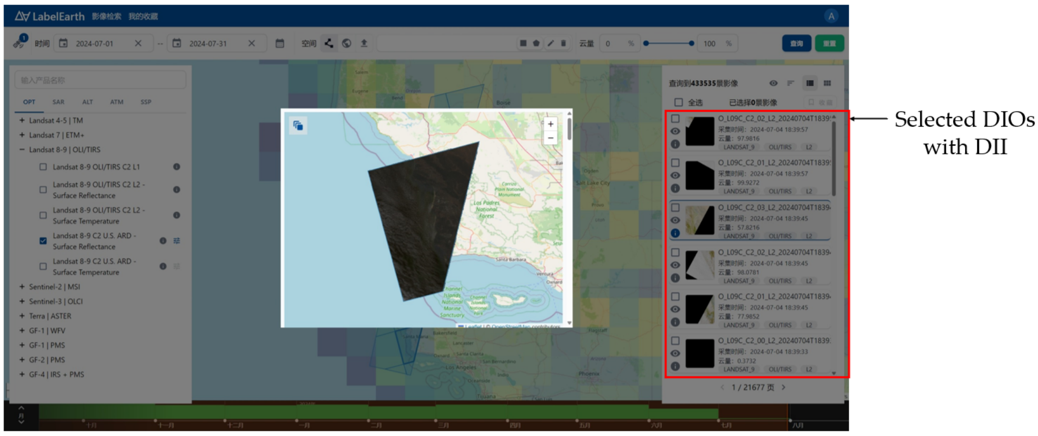

Figure 10. The interface showing the selected DIO result (the black area in the center).

5. Discussion

The digital image identifier (DII) proposed in this study is a globally unique identifier for digital image objects, designed around the acquisition start time of the image data, combined with satellite identifiers and product information. DII is both codable and parsable, setting it apart from existing naming conventions by mainstream satellite providers. Table 1 compares the naming approaches across major remote sensing imagery providers, focusing on time, space, and product information.

First, all satellite products universally include "image acquisition start time" as a core element, although additional time-related details vary by product type. DII also incorporates this key element. The study posits that the acquisition start time can uniquely determine the satellite position in orbit, enabling precise localization of the captured remote sensing data.

Second, current data products often include details such as orbit numbers, tile IDs, or the geographic coordinates of the product center. However, from the perspective of the inherent nature and essence of remote sensing imagery, this information may introduce redundancy in encoding. This study argues that spatial information can be inferred from temporal data. Hence, DII omits direct spatial information to streamline the encoding process.

Lastly, all satellite providers include "satellite/mission name" and "processing level" in their product naming schemes. Many also include sensor details or product-specific names, with some even combining both. DII integrates these elements to reflect product characteristics more comprehensively. Notably, dataset names are not universally included in existing naming systems. However, DII incorporates this aspect, ensuring applicability to the diverse range of remote sensing datasets worldwide. Given that almost all remote sensing data are now released in dataset formats, including this detail in DII is crucial for global compatibility.

The Product Tag is a distinctive feature of the DII framework. Recognizing the increasing customization of data products by institutions globally, especially for reprocessed products like ARD, the DII includes a product tag to distinguish such derived products from original imagery. These reprocessed datasets often lose the temporal uniqueness intrinsic to the original satellite imaging principles due to processing workflows. The product tag ensures that DII can capture the unique characteristics of such datasets, thereby extending its applicability to a wide array of remote sensing products.

In summary, the DII system is designed to overcome the limitations of conventional naming conventions, offering a scalable and globally applicable identifier that aligns with the evolving needs of the remote sensing community.

From the perspective of identifier design principles, compared with the naming rules of current major remote sensing imagery providers, DII global uniqueness is reflected in its unified coding system (Table 2). While the naming rules of satellite providers ensure the uniqueness of their remote sensing imagery data, these rules are not standardized globally. In contrast, DII achieves a unified coding system for all remote sensing imagery through a globally consistent encoding scheme. This gives DII an advantage in terms of comprehensiveness and completeness in naming.

Table 2. Comparison of principles among major remote sensing imagery providers and DII.

	Landsat 8 & 9	**MOD09**	**Sentinel-2A**	**Sentinel-3A**	**Sentinel-5P**	**Gaofen-1**	**Gaofen-5**	**Gaofen-7**	**DII**
Global Uniqueness	●	●	●	●	●	●	●	●	●
Scalability	●	●	●	●	●	●	●	●	●
Persistence									●
Normativity	●	●	●	●	●	●	●	●	●
Resolvable									●
Interpretability	●	●	●	●	●	●	●	●	●
Compatibility									●

Note: ● indicates whether the naming rules provided by the remote sensing imagery provider adhere to the principle. ● represents whether the DII naming framework complies with this principle.

Regarding scalability, all naming rules provide a guarantee for the naming of future data, and DII is also adaptable to the naming requirements of future data products. For permanence and interpretability, DII relies on an integrated platform, which ensures that data can be permanently accessed through auditing and registration, and accessed directly via DII. In comparison, although satellite providers offer corresponding naming rules at the time of data release, the naming might change when these data are stored by other organizations or platforms, thus not fully ensuring permanence. Additionally, many satellite providers simply name the imagery objects without providing a complete parsing system, making it difficult to directly interpret some data names and link them to corresponding imagery entities, so interpretability cannot be fully guaranteed.

In terms of interpretability, all remote sensing imagery data naming follows the principle of being interpretable, meaning that the names can clearly convey relevant information about the imagery. DII also adheres to this principle in its design, ensuring that its naming system has good interpretability. Regarding support for existing naming systems, while assigning a globally unique identifier, DII also establishes a mapping between the original encoding and imagery data entities in the background, ensuring compatibility with the naming rules of various satellite providers.

From the above comparison, it can be seen that DII not only ensures the uniqueness of global remote sensing imagery but also provides higher guarantees for permanence, interpretability, and openness, further improving the organization and access efficiency of remote sensing imagery data.

6. Limitations

This study acknowledges several limitations that require further exploration and refinement. First, it assumes that each digital image object corresponds to a unique storage location. However, in practical scenarios, a single image object may be stored across multiple locations (e.g., different storage platforms or servers). From the perspective of identity identification, these image objects, despite being stored in different locations, should share the same identifier because they originate from the same satellite identifier, product type, and acquisition time. This discrepancy highlights the need for a more comprehensive approach to handling multi-location storage while maintaining the consistency of unique identifiers.

Second, this study classifies satellite remote sensing image products into two broad categories: original image products and derivative products. For derivative products, the existence of the product tag code is essential. It ensures that when the metadata from other components of the DII cannot uniquely identify the data product, the production principle of the data can be used to designate a method for generating the corresponding product tag. This process requires a clear and detailed understanding of the production principles of derivative products, which could pose challenges for products with complex or opaque production workflows.

Finally, the current implementation of the DII encoding and parsing functionality is tightly integrated into the prototype system, limiting its accessibility to external applications or users. Future work should focus on standardizing this functionality to enable broader integration and easier use in other systems.

7. Conclusions and Future Work

With the exponential growth of satellite remote sensing data, there is an increasing global demand for more simplified and direct one-stop access to these datasets. This study introduces the concept of digital image objects (DIOs) from an object-oriented perspective and further proposes the digital image identifier (DII) framework. This framework encompasses encoding principles, structural design, encoding rules, and implementation methods. Experimental results demonstrate that the DII can uniquely identify digital image objects, support rapid parsing, and provide a solid foundation for the one-stop access, management, sharing, and trading of global satellite remote sensing data.

In future work, this study will first focus on effectively distinguishing between identical image objects stored in different locations and propose more refined data governance strategies and ownership mechanisms to ensure the accuracy, legality, and effective management of data.

Then, this study will also aim to further refine the DII encoding structure and rules. The current experiments do not encompass all satellite and sensor systems, nor do they account for the potential impact of these factors on the encoding rules. Thus, further efforts are needed to deepen and expand the existing encoding framework to ensure its applicability to a wider range of remote sensing products and to enhance its scalability and generalizability in practical applications.

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