JOURNAL OF INFORMATION SCIENCE AND ENGINEERING 37, 395-412 (2021)
DOI: 10.6688/JISE.202103_37(2).0008

A Space-Time Interactive Visualization Approach for Managing Remote Sensing Data

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With the rapid development of earth observation technology, the remote sensing data produced gradually shows characteristics of multi-source and heterogeneous, and data volumes are also exploding. Designing approaches and tools to manage the remote sensing data brings a unique set of research and engineering challenges, specifically with regards to data condition query and interpretation. First, we extract the metadata of the data to prepare for unified data retrieval. Considering the real-time, intuitive and interactive in data management, visual images are generated and used to represent the data itself. By considering the spatial characteristics of remote sensing data, we then propose a method based on mouse real-time plotting for the setting of spatial attribute condition, and the condition can be dynamically modified based on the feedback of the query result. After getting the query result, line frame and wall projection are used to display the data spatial distribution. For the intuitiveness and accuracy of data interpretation, we present an approach based on space-time cube technology to assess in a single view where remote sensing data with different parameters is unobstructed displayed in a layered manner. The approach consists of several parts, including a stack view, two cube boxes and a data probe. As an essential component, an information balloon is used to show data parameters and provide a convenient interface for data manipulation. Finally, we demonstrate the effectiveness and the usefulness of the proposed approach using a real-world case and three tests.

Keywords: remote sensing data, data query, visual interpretation, space-time cube, visualization

1. INTRODUCTION

With the rapid development of earth observation technology, a variety of remote sensing data has been produced. Due to different payload characteristics, processing algorithms, application purposes, *etc.*, the data has different parameters (metadata). Designing approaches and tools to manage massive, multi-source and heterogeneous remote sensing data brings a unique set of research and engineering challenges, specifically with regards to data condition query and interpretation.

To support the on-demand management of massive remote sensing data, the combination of database and 2D map and 3D globe have been established as a common approach, such as ArcMap and Google Earth. The database is used to organize and store remote

Received September 6, 2019; revised February 24, 2020; accepted March 30, 2020.
Communicated by Jimson Mathew.

sensing data in the form of metadata, and a 2D map and 3D globe are used to visually display the data. Note, in some current metadata-based data query systems, the setting method of the spatial attribute condition is relatively simple. The contemporary approach of a 2D map or 3D globe is often inadequate to support visuality and interactivity in the data management process. Specifically, previous studies usually show the data by the static overlay of its corresponding pyramid tiles, as demonstrated in Fig. 1. And this is exactly the way we used before. When viewing such display results, however, the visual impression for each data is difficult to intuitive establish, due to the huge amount that produces overlapping occlusion. At the same time, there is no more information on the spatial distribution of the data. These problems make it difficult to exert human subjectivity in data interpretation. However, in many data management cases, it is difficult to fully describe some of the requirements with metadata, but it is easy to visually judge whether the data meets the requirements. For example, a data manager needs to accurately and quickly retrieve data in a specific region and period. In particularly, the data must meet some specific quality requirements such as cloud coverage. In this example, the specific quality requirements require intuitive visual interpretation by humans.

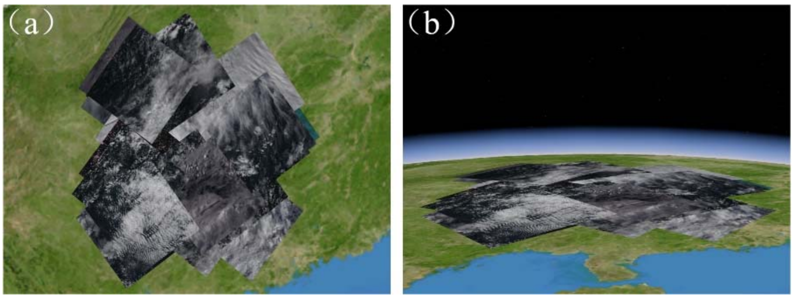


Fig. 1. The way of the traditional static overlay of pyramid tiles on the 3D globe; (a) Viewed from the top; (b) Viewed from one side.

In this work, we target to use the method of visualization to connect massive remote sensing data to human intelligence. we focus on three objectives in managing remote sensing data: (1) to design a visual and interactive method to facilitate the setting of spatial attribute condition; (2) to realize an intuitive and unobstructed visual presentation of each remote sensing data, including the spatial distribution of the data; (3) to realize the interactive data interpretation and convenient data manipulation. To achieve the aforementioned goals, we propose a method based on mouse plotting for the setting of the spatial attribute condition. The display of the data spatial distribution uses the way of line frame and wall projection [16]. The space-time cube [2] visualization technology is utilized to combine the time and space of remote sensing data so that the data is displayed in a layered manner. Some advanced identification tools are designed to facilitate the visual interpretation and operation of the data.

Our specific contributions are with respect to the following aspects:

- By considering the spatial characteristics of remote sensing data, we propose a method based on mouse real-time plotting for the setting of spatial attribute condition, and the condition can be dynamically modified based on the feedback of the query result.

- We present a visualization approach to assess in a single view where remote sensing data with different parameters is unobstructed displayed in a layered manner.
- For the intuitiveness and accuracy of data interpretation, we design two cube boxes and a data probe, which all support mouse interaction.

The rest of the paper is organized as follows: Section 2 is an overview of previous work in data management technologies related to this work. Section 3 is an overview of our method. In Section 4, we introduce the data used in our work and its pre-processing method. In Section 5, we elaborate on the design method of the data query model and the corresponding judgment rules. The visualization method of data spatial distribution is also presented in this section. In Section 6, we provide a detailed description of our space-time visualization approach to achieve intuitive and interactive data interpretation and manipulation. The use case of our method is demonstrated in Section 7. Finally, we conclude the paper and present future directions in Section 8.

2. RELATED WORK

Previous research related to the management methodologies of remote sensing data adopted in this paper includes data query and data interpretation.

With a series of features such as cross-platform, shareability and interoperability, metadata is widely used in various fields to explain and depict the content, quality, conditions and other characteristics of data. For remote sensing data, it is especially useful as it can reasonably match the difference of data parameters and provide conditions for unified storage and retrieval of data [11]. NASA's Earth Observing System Data and Information System (EOSDIS) uses structured metadata to describe the content and structure of its various categories of earth observation data, including remote sensing data [5]. Liu *et al.* [17] develop a remote sensing data management system for sea area usage management in China. In the system, a metadata interpreter tool allows data managers to classify the data products into categorical data types according to a set of domain-specific business rules. For the management of multiscale datasets encompassing airborne imagery and associated metadata, Ifimov *et al.* [14] present a multi-source geospatial database model based on the combination of the Relational Database Management System (RDBMS) and ArcGIS. Rasaiah *et al.* [23] present an approach to developing robust metadata standards that serves to ensure a high level of reliability and interoperability for a spectroscopy dataset.

Data query is an essential function that allows the user to retrieve data from one or more tables or expressions [4, 25]. For the query of remote sensing data, methods generally include using metadata as index [1, 3, 7, 13], extracting the image content and feature [24, 26, 27], combining semantics, metadata and image content [6]. Among these methods, the metadata-based method can effectively provide a unified data directory service for massive, multi-source and heterogeneous data, and can avoid direct manipulation of a large amount of "original data", is widely used as the basic way of data query. The spatial attribute is especially helpful to the query of remote sensing data, for it can take full advantage of the spatial characteristics of the data. The spatial attribute is generally converted into metadata to participate in the data query. Typical solutions use the textbox or drop-down option as the input method to set the spatial attribute condition [8]. Alonso *et al.* [1] introduced a polygon-based region selection method in their work, which allows users to focus the analysis in a specific area of interest. In this paper, we adopt metadata as the basic way of data query, extend the polygon-based method and provide four types of region setting methods based on mouse real-time plotting. This allows more flexibility and precision in setting the spatial attribute condition.

The visual interpretation of remote sensing data has been proved particularly effective in applications like data definition judgment, data stripe judgment and data feature change judgment. For VAST Challenge 2017, Malla *et al.* [21] developed a tool that can display each band of multi-spectral images as a grayscale image. It also has the flexibility of mapping individual bands to the red, green and blue channels of the displayed image. With image pan and zoom in/out function, the tool is used in identifying land features as well as assist in finding changes over time in their work. The same is for VAST Challenge 2017, Mahida *et al.* [19] provided a satellite image analysis tool that combines small multiple views of images, linked semantic zooming, *etc.* Among them, small multiple views allow users to intuitively interpret the changes in images across seasons. Lobo *et al.* [18] used animation to intuitively show the evolution of a given region between before-and-after satellite image pairs over a specific period. Early remote sensing software, such as ENVI, has already been able to display remote sensing data and can perform visual analysis on data [9, 15]. However, since it is a direct operation of the "original data", it is not suitable for simultaneously opening a plurality of data, and cannot be used for data management operations such as virtual interpretation. Especially, common 3D globes such as Google Earth support visualizing remote sensing data by loading pre-processed pyramid tiles and is widely used for the virtual display of massive remote sensing data [12, 20, 22]. The shortcoming is that these systems are only used for the virtual display of remote sensing data, and have the problem of overlapping occlusion so that the visual interpretation of the data cannot be performed. The space-time cube is used in various fields, and many successful applications have proven its important value [4, 10, 16]. Bach *et al.* [2] provided a thorough overview of the space-time cube and the application-specific variations. We provide a visualization technique that built upon the concept of space-time cube to support display for efficient visual interpretation of massive, multi-source and heterogeneous remote sensing data without occlusion.

3. WORKFLOW OVERVIEW

Our proposed visualization method enables users to perform on-demand management operations of massive, multi-source and heterogeneous remote sensing data, such as data condition query and visual interpretation. Fig. 2 shows an overview of the proposed workflow.

Our approach starts with the pre-processing of a set of remote sensing data, including the extraction of metadata, the generation of visual images and the data storage in Fig. 2 (a). In this work, we adopt metadata to uniformly describe the heterogeneous remote sensing data and use a spatial database to store metadata and provide unified data service. For the data files and their visual images, we consider a distributed file system for storage. The next step is to set the query conditions including text parameter condition and spatial attribute condition in Fig. 2 (b). The text parameter condition is implemented using metadata as a basic condition of data filtering. We extend the polygon-based method and provide four types of spatial attribute condition setting methods based on mouse real-time plotting.

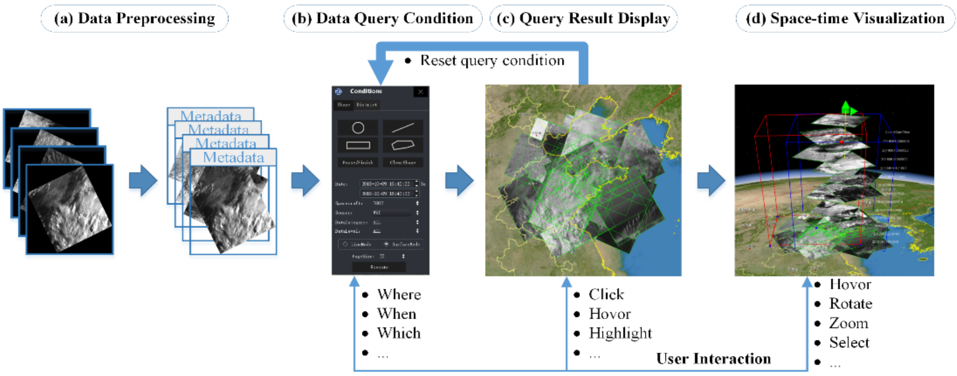


Fig. 2. Method overview; (a) Data pre-processing; (b) Data query condition; (c) Query result display; (d) Space-time visualization with user interaction.

After executing the query command, we get a set of eligible data. The query result is displayed on the 3D globe in the form of a traditional static overlay of pyramid tiles. In addition to display the query result directly, adapted the idea of projection walls along the time axis from the work of Kurzhals *et al.* [16], the spatial distribution is encoded and intuitively displayed on the 3D globe in two different ways in Fig. 2 (c). Even though many visualization methods can be used to display the remote sensing data, we provide a method that built upon the concept of space-time cube in Fig. 2 (d). Our method with some advanced identifications can well support the unobstructed display of massive remote sensing data for efficient visual interpretation. The scene can be zoomed in/out and rotated by mouse operation.

We believe that our approach can significantly help to improve and accelerate the management of massive, multi-source and heterogeneous remote sensing data. In particular, we demonstrate that our approach has significant advantages over data management in the form of pyramid tiles since it can produce visual occlusion. We demonstrate the effectiveness of our approach with real-world data management requirements proposed by our data users.

4. DATA PRE-PROCESSING

4.1 Data Description

To demonstrate the effectiveness of our approach, this paper focuses on a real remote sensing dataset derived from October 1, 2011 to April 1, 2019 by Tiangong-1 spacecraft and Tiangong-2 spacecraft. The dataset has the following characteristics:

- Multi-source (Diverse data categories): The remote sensing data contained in the dataset is derived from different earth observation payloads, such as wide-band imaging spectrometer and interferometric imaging radar altimeter. The working principle of sensors carried by the payloads is also different, so the data categories are different, such as visible and near infrared spectrum data, short wavelength infrared spectrum data and thermal infrared spectrum data.
- Large volume: The data contained in the dataset has a large period, a large number and a large total size. The size of individual data is also large.

The individual remote sensing data contains the following parameters:

- Time: Each data has three time parameters, namely observation time, reception time and processing time. The observation time and reception time of each data are unique. A data can be processed multiple times to generate multiple data with different processing times.
- Space: The data has a spatial attribute that reflects the ground coverage. The spatial attribute is identified by four coordinate points, expressed in latitude and longitude.
- Event: The content of the data reflects the ground information of a certain time and a certain area, such as cities, mountains, rivers and even forest fires.
- Processing parameters: Due to the variety of data categories, different parameters will be set during different processing, such as data level, bad pixel and standard scene.
- Band: Band is a special parameter. According to the working principle of the sensor, the data collected by different sensors have different numbers of bands, such as visible and near infrared spectrum data has 14 bands, short wavelength infrared spectrum data has two bands. Each band represents a different physical meaning. This makes the traditional image viewer cannot open the data directly, which is one of the reasons that we generate visual images.

4.2 Data Pre-processing

As can be seen from the data description, the data categories in the dataset are various, and each category has its defined parameters. To be able to perform unified data service and visual interpretation, we extract the metadata of the data. Specifically, the parameters with the high frequency of use in data management such as time, space and data level are extracted and normalized, and as the basis for data condition query and visualization.

Considering the real-time, intuitive and interactive in data management, this paper generates the visual images of remote sensing data and uses the visual images to represent the data itself. One or three bands that reflect the overall appearance of the data are extracted from a series of bands according to the data category. The format of the visual image is PNG (Portable Network Graphic). For example, three bands of 8, 10 and 12 are extracted as RGB channels from visible and near infrared spectrum data in Fig. 3 (a). Since short wavelength infrared spectrum data has only two bands, the first band is extracted to generate a grayscale visual image in Fig. 3 (b). In the process of generating visual images, we adopt the histogram equalization algorithm to enhance the visual effect, and at the same time, the invalid area is set to be transparent.

(a) (b)

Fig. 3. Illustration of the generation of visual images; (a) Three bands of 8, 10 and 12 are extracted as RGB channels from visible and near infrared spectrum data; (b) The first band is extracted to generate a grayscale visual image from short wavelength infrared spectrum data.

Data storage is an important part of remote sensing data management, but it is not the core focus of this paper. Here, we only briefly explain it. To ensure the real-time of data condition query, we use the PostGIS spatial database to store the metadata. To ensure the efficiency of the read request of visual images in the case of increasing data amount, we use MongoDB to store a huge number of visual images.

5. DATA QUERY MODEL

5.1 Data Query Model Design

The data query model is a prerequisite for space-time visualization of remote sensing data and is designed to enable an on-demand query. We draw on the definition of the atomic query in [4] to divide a query model into three components: query condition, query operation and query result. In our approach, the query condition consists of two different types, one of which we call text parameter condition, such as time (when), spacecraft (which), sensor (which), *etc.*, another type we call spatial attribute condition, including shape (where) and district (where). It should be noted that in a query operation, only one of shape and district can be selected. In a query operation, we follow the query constraint of equation3 in [4], that when+which+where→result. The query result is a set of data that meets the query condition, consisting of metadata and visual images.

Due to the particularity of the spatial attribute condition, we focus on explaining how it operates and works. The shape condition uses the mouse to click and drag on the 3D globe to draw the region or path, specifically including line segment, circle, rectangle and polygon (Fig. 4). The region of district condition is determined by pre-set SHP (Shapefile) data, for example, the China region can be selected, or a province of China, Shandong Province, can be selected as the district condition. The district condition can be treated as a special shape condition.

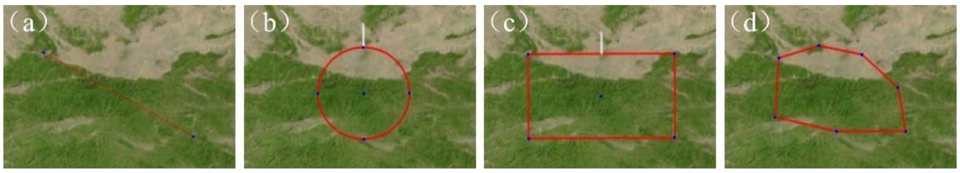


Fig. 4. Illustration of shape condition; (a) Line segment; (b) Circle; (c) Rectangle; (d) Polygon.

A remote sensing data has four coordinate points, expressed in latitude and longitude. The four coordinate points and the four edges they form describe the coverage of the data. After analyzing the actual management requirements of remote sensing data, we made the following rules:

- Line segment: When the coverage of a remote sensing data intersects with the line segment, we determine that the data satisfies the spatial attribute condition. As shown in Fig. 5 (a), data A and data C intersect with the line segment, so they satisfy the condition and will be added to the query result. Data B and data D do not intersect with the line segment and therefore do not satisfy the condition.
- Circle, rectangle and polygon: Taking rectangle as an example, when at least one of the

four coordinate points is within the rectangle, or at least one of the four edges intersects with the rectangle, we determine that the data satisfies the spatial attribute condition. As shown in Fig. 5 (b), the red wireframe represents the rectangle, data A with a coordinate point (a1) in it, data B with all four coordinate points (b1, b2, b3 and b4) in it and data D with an edge (d1 to d2) intersects with it satisfy the condition and will be added to the query result. Obviously, data C does not satisfy the space attribute condition.

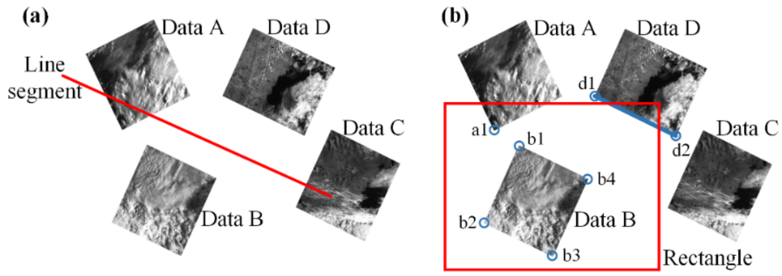


Fig. 5. Illustration of the satisfaction of spatial attribute condition; (a) Rule of the line segment; (b) Rule of the rectangle.

5.2 Query Result Display

The query result is displayed on the 3D globe in the form of a traditional static overlay, as shown in Fig. 1. Presenting the data range identification on the 3D globe can give an impression of the data amount and especially the spatial distribution of the data. Following the way of wall projections for the gaze tracking in [16], the spatial distribution of data in the query result is displayed. Our approach also handles the range identification in a 2D manner, but displays on the 3D globe. The range identification of a remote sensing image data is calculated from its four coordinate points. To display the range identification of each data, we propose two different modes, one is wireframe mode and the other is semi-transparent patch mode. Fig. 6 shows the two modes. In the semi-transparent patch mode, the patch of each data is semi-transparent. If multiple patches are displayed at the same time, the multiple patches are superimposed on each other, and the transparency decreases

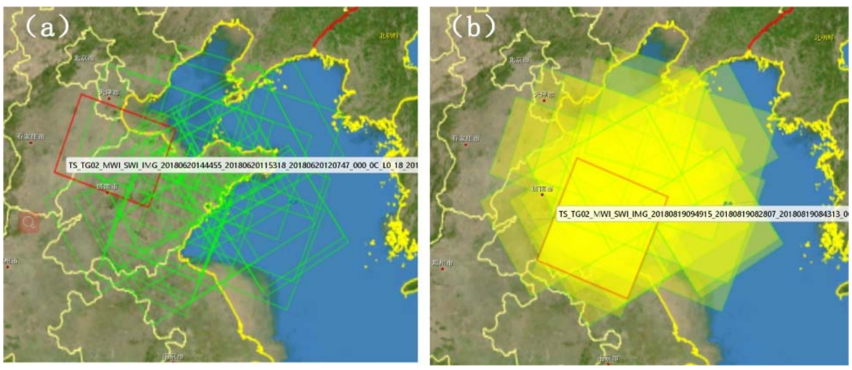


Fig. 6. Illustration of two different range identification modes; (a) Wireframe mode; (b) Semi-transparent patch mode.

as the number increases. The change in transparency can be used to determine the amount of data. The range identification will be highlighted if the mouse is hovering on it, and the data name will be displayed. The display of the query result can, in turn, help us modify the query condition.

6. SPACE-TIME INTERACTIVE VISUALIZATION METHOD

The management of remote sensing data can be implemented in various ways. Commercial management tools provide visualization methods that are widely used with some disadvantages in actual usage, especially in data interpretation. The major problem is that as the amount of data increases, the phenomenon of visual occlusion becomes more and more serious. To alleviate these problems, we propose an alternative visualization technique that built upon the concept of space-time cube [2].

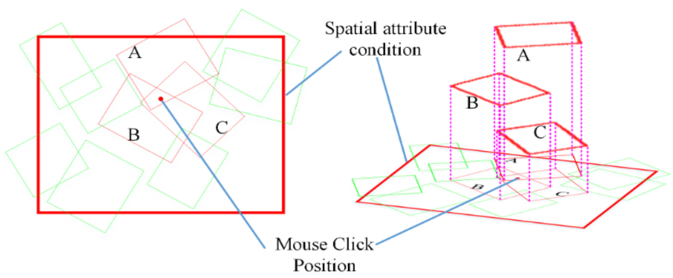
The method is composed of three interrelated parts: (1) Stack view: which enables a view with almost no mutual occlusion on the visual images in the stack. Stack view visualization is the first step and foundation of the method; (2) Advanced identification: including two cube boxes and a data probe. The cube box identifies the boundary of the spatial attribute condition and the boundary of the visual images in the stack view in a stereoscopic manner to assist in further data interpretation. By moving the position of the data probe, it is possible to quickly determine which data covers the position of the probe and provide a position reference for the interpretation; (3) Parameters show: which provides detailed information of the data clicked by the mouse, and provides direct data manipulation buttons.

6.1 Stack View

One of the important tasks in remote sensing data management is the visual interpretation. Especially when the purpose of the interpretation is to identify the data that meet some specific quality requirements. Ferstl *et al.* [10] studies stacked time-cuts to visually show changes in weather in meteorological data sets. Following their study, we designed a stack view, which can visually present the overall perspective of the data to users. The stack view is based on the 3D globe as the carrier, where two dimensions refer to space and the third dimension refers to time.

First, we need to determine which visual images are added to the stack view. In the actual data interpretation process, the user tends to pay attention to a small area and even a point, so we use the position of the mouse click on the 3D globe as the basis for judgment. Traversing all visual images in the query result, if the coverage of one data contains the mouse position, the visual image will be added to the stack view for visualization in Fig. 7 (a). The visual images in the stack view is a subset of the query result, which is dynamically changed based on mouse click interaction.

In the stack view, according to the order of observation time and processing time, the visual images are sequentially arranged from the bottom to the top. The observation time of each corresponding remote sensing data will be displayed on one side of the stack view. The visual images in the stack view only move in the vertical direction, and their horizontal position is consistent with the corresponding data. Although the observation time is not equal time interval, the visual images are arranged in the vertical direction at an equal interval according to a pre-set value. This is depicted in Fig. 7 (b). After sorting by time, the stack view also can help to initially determine the change of the ground information over time.



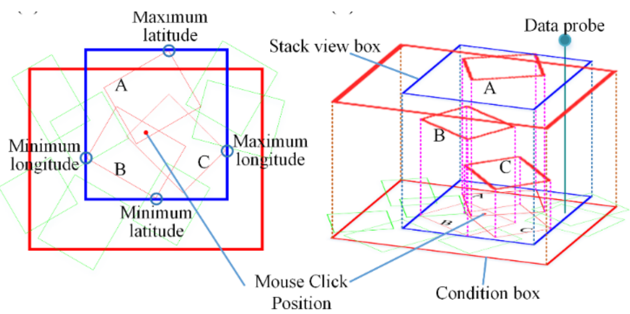
(a) (b)

Fig. 7. Illustration of the stack view; (a) Viewed from the top. A total of 10 data satisfy the spatial attribute condition. Among them, the coverage of Data A, Data B and Data C respectively contains the mouse click position, therefore, the three visual images will be added to the stack view; (b) Viewed from one side. The three visual images are sequentially arranged from the bottom to the top at an equal interval.

If the mouse clicks on another position on the 3D globe, the visual images in the stack view will be updated. In the design of the stack view, we need to consider many visual images that need to be visualized at once. In this case, the phenomenon of mutual occlusion will still occur. The stack view is improved so that it can be stretched or compressed vertically, and the spacing between visual images will be smoothly expanded or reduced.

6.2 Advanced Identification

With the stack view, however, sometimes it is still difficult to identify the spatial relationships between the data in the stack view and the data in the query result because no common flag is given in the stack view. Therefore, we slightly modify and enhance the stack view by adding two cube boxes and a data probe in Fig. 8.



(a) (b)

Fig. 8. Illustration of two cube boxes; (a) Viewed from the top; The values of four coordinate points of the bottom of stack view box are constructed by the maximum latitude, the maximum longitude, the minimum latitude and the minimum longitude of Data A, Data B and Data C; (b) Viewed from one side. The height of two cube boxes is the same, and equal to the height of Data A.

One box is based on the space attribute condition as the vertex coordinates, called the condition box. The line color of the condition box is displayed in red. The other box is the range box of the visual images in the stack view, called the stack view box. The line color of the stack view box is displayed in blue. The method for determining the values of four coordinate points of the bottom of the stack view box is shown in Fig. 8 (a), that is, the values are constructed by the maximum latitude, the maximum longitude, the minimum latitude and the minimum longitude of all visual images in the stack view. The height of two cube boxes is the same, and equal to the height of the highest visual image in the stack view in Fig. 8 (b).

The vertical faces of two cube boxes will change transparency as the mouse strokes. A silhouette is drawn for each visual image. When the mouse is hovering on a visual image, the color of its silhouette will change from green to red, and its name will be displayed in the form of a floating frame. Next, if the user wants to analyze the data coverage of a position of interest, they can use what we call the data probe. The data probe is a line segment perpendicular to the ground, and its length dynamically changes with the height of the stack view in Fig. 8 (b). When the user picks up the data probe through the mouse, the data probe will be highlighted in red and change its position as the mouse moves. With the advanced identification, users can interactively and intuitively judge the spatial relationships of the data.

6.3 Parameters Show

As described in Section 4.1, different categories of remote sensing data have different parameters. Through the stack view and its advanced identification, users can interpret the data quality and spatial relationships, but still cannot fully grasp all the parameters of a data. To provide to users an overview of the parameters of a data (Width, Height, Geometric Correction, Bad Pixel Replace, *etc.*), we use a translucent information balloon in Fig. 9. The information balloon uses a floating dialog to support the dynamic display and hidden employing the mouse click on a visual image and provides convenient data selection and download manipulation, to let the user select or download a data by clicking on the respective button. Using the floating information balloon, rather than opening a new static dialog, makes it easier and more flexible to view the parameters of the data.

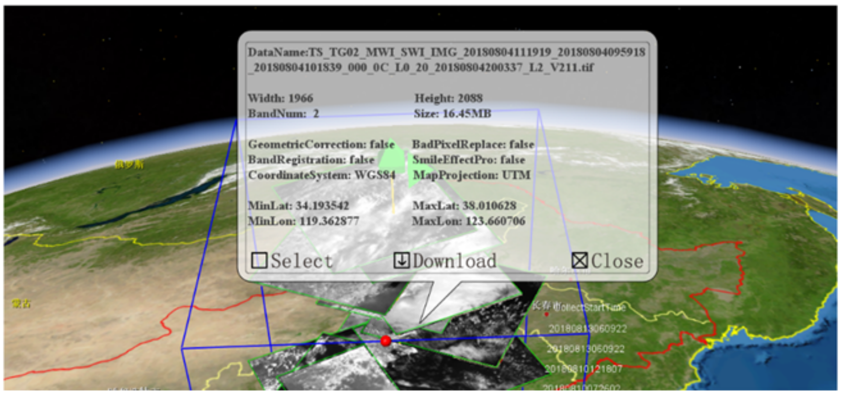


Fig. 9. The floating information balloon is used to display the parameters of the clicked data.

7. USE CASE

The interactive visualization method including stack view, cube boxes, information balloon, *etc.* has been implemented and integrated into our data management system, which is based on the open-source visualization tool WorldWind. WorldWind provides a suitable infrastructure that already included a 3D globe and various visualization interfaces, such as images, lines, text, *etc.* For the computation of the visual images, our implementation uses the library GDAL. PostGIS spatial database is used to store metadata. MongoDB is used to store a huge number of visual images. A DEM (Digital Elevation Model) layer and an administrative division data layer are added to the 3D globe to help data visual interpretation. The data we manage is derived from different earth observation payloads of Tiangong-1 spacecraft and Tiangong-2 spacecraft. All presented results were generated on a standard desktop PC with an Intel i7 CPU, 8GB CPU memory, and GeForce GTX 1080 with 8GB GPU memory. Fig. 10 is a complete screenshot of the system with this method.

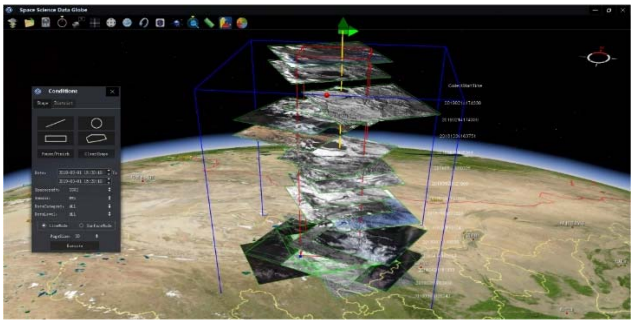


Fig. 10. A complete screenshot of the system with this method.

To demonstrate the effectiveness and the usefulness of the proposed approach, we discuss a real-world case that often occurs in daily data management work. The example examines the retrieval of data that covers a lake in China - Qinghai Lake as a demonstration. Of course, some requirements are put forward for the required data, including: (1) the data is derived from wide-band imaging spectrometer of Tiangong-2 spacecraft; (2) the period is from March 1, 2018 to March 1, 2019; (3) the data has no stripe problem; (4) the cloud of the data cannot affect the judgment of the ground information; and (5) the coverage of each data can completely cover the target area. This example is a real case, one of the data users once presented to us. After a full analysis of the requirements, the query and interpretation procedure consist of several necessary steps in Fig. 11.

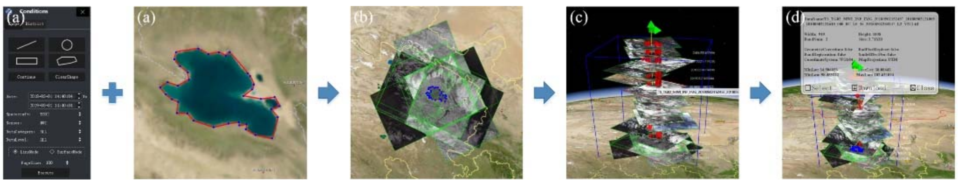


Fig. 11. Illustration of the whole procedure; (a) Set the data query model according to the user's requirements, including text parameter condition and space attribute condition; (b) Execute the query command and visualize the query result directly on the 3D globe; (c) Interactive data interpretation with stack view; (d) Show parameters and select/download data.

Step 1, set the data query model according to the user's requirements, including the text parameter condition and the space attribute condition. In this case, the setting of the text parameter condition includes time and payload. Since the shape of our target area - Qinghai Lake is an irregular polygon, we chose the polygon to draw the required spatial attribute condition on the 3D globe in Fig. 11 (a).

Step 2, execute the query command and visualize the query result. The query result is some data that matches the query condition, which is directly displayed on the 3D globe in Fig. 11 (b). The data obtained at this step often has the following problems: (1) some data has the stripe problem; (2) some data is covered by too many clouds; and (3) not all data coverage can completely cover the target area. At this step, although all the data is displayed on the 3D globe, it is impossible to intuitively interpret the data due to the serious overlap.

Step 3, interactive data interpretation. The problems in Step 2 need to make an intuitive interpret. The stack view is displayed by the mouse clicking on the 3D globe in Fig. 11 (c). Using the stack view, we visually interpret the data. Since there are many visual images in the stack view, we first stretch the stack view vertically to reduce the mutual occlusion phenomenon in Fig. 12 (a). Obviously, through the stack view, we know that some data do not meet the requirements for the stripe problem in Fig. 12 (b). Next, we interpret the ambiguous plots by controlling the rotation and zoom of the 3D scene. After doing a close observation, we know that some data has too many clouds in Figs. 12 (c) and (d), so these data do not meet the requirements. In interpreting the coverage of data, we improve the efficiency by hovering the mouse over the condition box to make the vertical surface semi-transparent in Fig. 12 (e). After moving the data probe to the edge of the data, we further interpret the coverage of the data more accurately and know that some data do not meet the requirements for completely cover the target area in Fig. 12 (f). Through interactive interpretation, we finally determine which data is eligible and see the name of the data by highlighting its silhouette in Figs. 12 (g) and (h).

Step 4, select and download data that meets the requirements. For data that satisfies the user's requirements, we open the information balloon and do a detailed interpretation of the parameters, and decide whether to select and download it in Fig. 11 (d).

In this case, through several steps, we successfully get the data that meets the user's requirements. To show the effectiveness of the system, we conducted the following tests and kept a detailed record of how long it took in each test to get the data that meets the user's requirements described above.

Test 1: Use a 2D map-based condition retrieval system to query the data in Fig. 13, which is the most common data management system. In this system, the space attribute condition must be set to a circle or a rectangle, which is much larger than the actual range of Qinghai Lake. As a result, a large amount of apparently irrelevant data will be retrieved. At the same time, we need to click on each data to open a new page to interpret the status of the data. What's more, we cannot visually judge whether the range of a data can completely cover the target area. We need to use commercial software, for example, ENVI, to do this work.

Test 2: Use our previous version of the data management system based on the 3D globe to query the data, as shown in Fig. 1. Compared to Test 1, we can use a polygon to set the space attribute condition more accurately. However, due to the overlap of each data, we still difficult to intuitively establish the visual impression for each data. This constrains our interpretation of the status of the data.

Test 3: Use the system with the methods of this article to query the data. Because we can intuitively establish the visual impression for each data, and combined with flexible interaction, we can get the data that meets the user's requirements quickly.

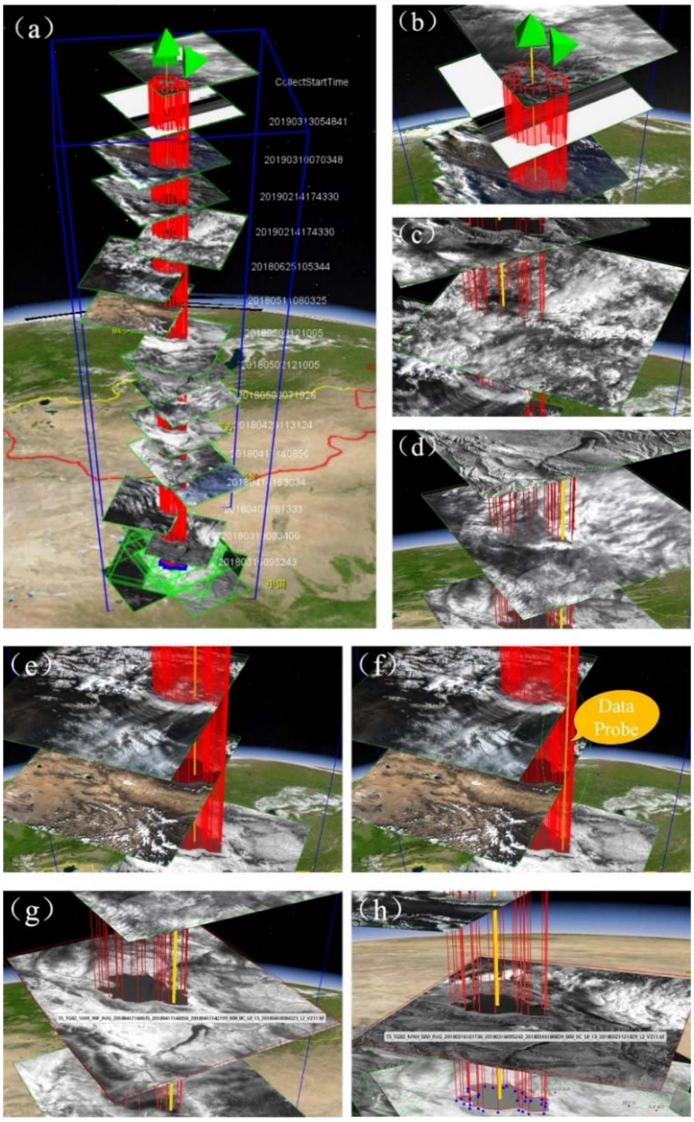


Fig. 12. Interactive data interpretation; (a) Stretch the stack view vertically to reduce the mutual occlusion phenomenon; (b) A data with stripe problem; (c) and (d) Data with too many clouds; (e) In interpreting the coverage of data, through hovering the mouse over the condition box to make the vertical surface semi-transparent display; (f) Through moving the data probe to the edge of the data, it is more accurate to judge that some data do not meet the requirements for completely cover the target area; (g) and (h) Data that meets the requirements.

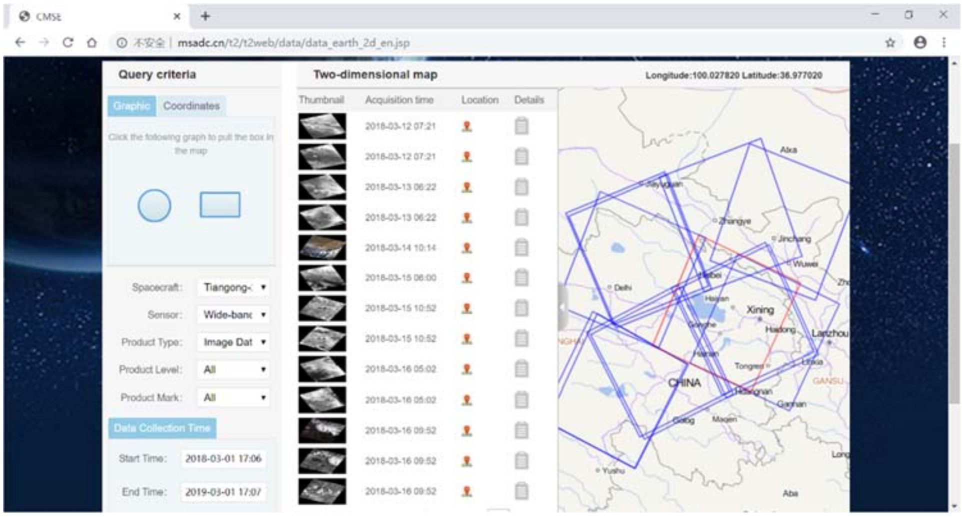


Fig. 13. Use a 2D map-based condition retrieval system to query the data.

Table 1. The time it takes to get the data. (Unit: minutes).

	Test 1	Test 2	Test 3
Time	52	30	18

Table 1 shows the experimental results. Due to the case described above is a typical example of the data requirement, we have reasons to believe our system can greatly improve the efficiency of daily data management work.

8. DISCUSSION AND CONCLUSION

Compared with previous data management methods, in this paper, we have presented a novel approach for managing remote sensing data through a space-time visualization in combination with flexible interaction. A visually assisted data query model, the space attribute condition, in particular, is introduced as a foundation for data query. With the stack view, its advanced identification and the information balloon, our design achieves high efficiency in terms of data interpretation and data manipulation. The use case studies demonstrate the unique capabilities of our approach. Our approach has been successfully applied in the management of data derived from different earth observation payloads of Tiangong-1 spacecraft and Tiangong-2 spacecraft. The implemented system provides a unified query and visual interpretation of massive, multi-source, and heterogeneous remote sensing data for users. At present, this system is frequently used in our daily data management work, and greatly improve our work efficiency. We are also expanding the data categories supported by the system to prepare for managing the data derived from the payloads of the upcoming Chinese Space Station.

For future work, we plan to research to combine quantitative data interpretation algorithms with visual interpretation methods to reduce the workload of visual interpretation and make up for the ambiguity in visual judgment. Especially with the development of deep learning technology, it provides a good solution to this problem. We also intend to explore more flexible interaction methods, making the query and interpretation for massive remote sensing data simpler and more user-friendly.

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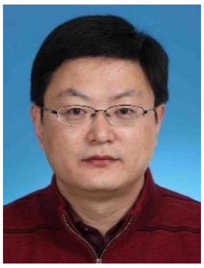

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