Multiple-view geospatial comparison using web-based virtual globes

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ABSTRACT

Existing virtual globes, including both unique platforms and associated visualization applications, often present geospatial information with a single-view mode that restricts the user to a single dataset. Due to the absence of the functionality and user interface for coordinating multiple virtual-globe views, it is either hard or impossible to explore multiple different geospatial datasets simultaneously only using the existing virtual globes, especially when the datasets come in multiple sources, multiple spatial resolutions or multiple temporal scales. Here we present a general visualization framework that supports the exploration and comparison of various datasets with multiple coordinated views in the web-based virtual globe environment. This framework not only comprehensively considers the dynamic master/slave relationship between multiple virtual globes, but also effectively handles the coordination mechanism for diverse views to respond to users' manipulations. We also implement a prototype application (termed MultiGlobe) and demonstrate its effectiveness over three typical application scenarios. The first case addresses the comparison of diverse imagery layers derived from different providers. A second case is examining multiple digital maps for a specific region or theme, such as time-varying LUCC datasets. As a final example, we compare and evaluate the accuracy of multiple DEMs generated from diverse data sources with different resolutions. Our informal evaluation with experts in exploratory visualization and spatial analysis confirms that the multiple-view-enhanced virtual globe can bring many benefits including focusing on spatial awareness, reducing cognitive efforts, coordinating interaction strategies, increasing browsing speed and enhancing comparison capabilities. Therefore, it can be incorporated into a variety of geospatial visualizations to replace or supplement the fixed single-view interfaces of the traditional virtual globe applications, empowering users with the ability to explore and compare multiple different datasets across the same geospatial area synchronously.

1. Introduction

Over the past two decades, web-based virtual globes (Blaschke et al., 2012; Butler, 2006; Gore, 1998), such as Google Earth (Google Inc., 2005a), NASA WorldWind (NASA Ames Research Center, 2004), Cesium (Analytical Graphics Inc., 2011), and other online Earth browsers (Keysers, 2016; Mahdavi-Amiri et al., 2015), have been widely embraced by Earth scientists of various disciplines as convenient tools to enhance science for various application scenarios, including integrating geospatial information, improving visualization capabilities, exploring spatio-temporal changes, and communicating scientific results (Bailey and Chen, 2011; Ballagh et al., 2011; Bladin et al., 2018; Chen et al., 2016; De Paor et al., 2017; De Paor and Whitmeyer, 2011; Goodchild et al., 2012; Li and Wang, 2017; Liang et al., 2018; Muller et al., 2016; Schiewe and Madden, 2010; Tiede and Lang, 2010; Trubka et al., 2016; Yu and Gong, 2012; Zhu et al., 2014). As organizing

metaphor of the Earth's surface, virtual globes not only offer users the capability to explore high-resolution images and terrain data on different spatial scales, but also can be used to integrate, visualize and analyze user-generated remote sensing imageries, terrain data, 3D models and other custom geospatial information in a variety of formats (Liu et al., 2015; Triantafyllou et al., 2017; Zhu et al., 2016, 2018a). By changing their viewing angles and positions, users can freely move around within the virtual environment provided by virtual globes, explore and analyze geospatial information from different perspectives and at different detail levels.

With the continuous evolution of geospatial information acquisition technology, Earth scientists began to conveniently capture, store and process vast quantities of geospatial datasets to reveal varieties of environmental and cultural phenomena on the Earth (Boyd et al., 2018; Han et al., 2015; Zhu et al., 2018b). Prominent examples of geospatial datasets include remote sensing imageries derived from various Earth

observation satellites (Sandau et al., 2010), digital elevation models (DEMs) with different resolutions obtained from a variety of satellite sensors (Alganci et al., 2018; Zheng et al., 2017), and global/local digital maps produced by different individuals, companies, academic institutes or government organizations (Gore, 1998; Han et al., 2015). These datasets are characterized as being multi-source, multi-resolution and multi-temporal, and thus, can be imported into a georeferenced virtual globe platform for exploring and analyzing spatial or temporal relationships/correlations hidden behind them to produce new knowledge. In order to investigate these datasets more effectively, it is often necessary to employ advanced visualization mechanisms that allow users to explore multiple datasets synchronously. The user may wish to compare and analyze multiple datasets within a given spatial area and conduct frequent viewpoint movements and scale changes to find differences, changes, or links between those datasets. However, traditional virtual globes, including both unique platforms and associated visualization applications (Keysers, 2016), tend to provide a single-view mode for presenting geospatial information. There are several shortcomings and a number of serious limitations when using the existing single-view virtual globes to explore, compare, and analyze multiple geospatial datasets. For example, when exploring a dataset, the user may want to open another dataset, explore and compare it with the previous one without overlapping views. However, the current single-view virtual globes restrict the user to a single dataset. To progress the work, the user must decide whether to close the previous dataset or to drape the new dataset over the preceding one in the current default single-view window. Obviously, by doing so, the user has to explore, compare, and analyze these two datasets subconsciously and would lose or restrain geospatial information provided by the previous dataset either implicitly or explicitly. Thus, it is difficult for the user to find and understand the similarities and differences between these datasets.

One potential solution to this problem is to create two or more stand-alone virtual globe instances at the same time. Each instance presents a virtual-globe window in which an individual dataset can be loaded and displayed. However, in this situation, it is either hard or impossible to coordinate the interactive operations on those instances because each instance is an independent program. When exploring a dataset in a virtual globe instance, the user's interactions or manipulations within the current window cannot be synchronized to other virtual globe instances automatically. In order to show the same spatial area within other virtual globes, the user has to handle those globes one by one manually. This both reduces users' browsing speeds and increases their cognitive efforts. Thus, it is not appropriate in cases where coordinated operations on multiple virtual globe instances are required.

To overcome the above limitations on exploring and comparing multiple geospatial datasets, a more straightforward, intuitive and accessible solution can be achieved by using coordinated multiple views (CMV). As a specific visualization technique that enables users to effectively and intuitively collate, compare, hypothesize, manipulate and present their datasets in the exploratory visualization environment, CMV is used to describe the situation where a group of (two or more) ordered views are created to present multiple different but related datasets, or multiple different representations of the same dataset, and hence the user's manipulation in each view is linked to that of any others, maintaining formal or substantive coordination automatically (Andrienko and Andrienko, 2007; Griffin and Robinson, 2015; Roberts, 2007). Specifically, for the web-based virtual-globe application scenario, multiple virtual-globe views can be generated to display the same spatial area synchronously, and each view only shows a particular aspect of the geospatial information within the given area, such as a dataset derived from a particular data source or with a particular spatial/temporal resolution. Therefore, in virtual globes CMV usually means displaying multiple different datasets within the same spatial area, presenting users with more information and parameter choices, managing users' manipulations on each view, as well as automatically coordinating their behaviors between multiple windows. By utilizing

multiple views to present multiple datasets, the user can easily explore and compare their datasets fallen into the same area from two or more perspectives, especially when the datasets describe the distinctive aspects of the same features.

Since the First International Conference on Coordinated and Multiple Views in Exploratory Visualization was held in 2003 (Roberts, 2003), the academic community and industry developers have launched a series of explorations on how best to utilize CMV to represent and analyze geospatial information within an exploratory visualization environment. The related research involves two essential aspects: theories and models for CMV, and applications of the CMV visualization technique.

In the realm of theories and models for CMV, the past research has focused on visualization forms of the views, coordination models/architectures for multiple views, and interaction techniques for multiple coordination views. A variety of visualization forms (Golebiowska et al., 2017; Roberts, 2007) were suggested and implemented in the multiple-view environment to assist users in presenting their datasets in various ways. In order to depict the inter-relationships between multiple views and multiform representations, several creative display modes for multiple views, such as the dual-view visualization (Convertino et al., 2003; Han et al., 2015) and its variants (Roberts, 2007), have been developed and applied. Besides, considerable effort has been given to develop effective coordination models. A variety of modeling and architectural approaches, such as the constraint approach (McDonald et al., 1990), the data-centric approach (North and Shneiderman, 2000), the Model-View-Controller approach (Pattison and Phillips, 2001), the shared coordination object approach (Boukhelifa et al., 2003; Boukhelifa and Rodgers, 2003) and the visual abstraction language method (Weaver, 2004), were proposed to formally model coordination in multiple linked views (Widjaja et al., 2015). Moreover, there are two kinds of interaction techniques that can be incorporated into CMV systems (Roberts, 2007): one is the indirect manipulation technique that utilizes sliders, buttons, and menus to constrain the viewed datasets and change their display methods, and the other is the direct manipulation technique that allows the user to interact with the visualization objects directly by utilizing the mouse, the handle and other hardware devices.

In the realm of the applications of CMV, the past research has focused on developing CMV tools, applying these tools to different application contexts, and evaluating the usability and perception of visualization results through multiple-view tools. Some developers have been created a number of visualization tools to support CMV, including both the specific toolkits and the general systems (Andrienko and Andrienko, 1999; Hardisty and Robinson, 2011; North and Shneiderman, 2000; Stalling et al., 2005; Takatsuka and Gahegan, 2002; Weaver, 2004). These tools have been widely used in a number of fields, especially in the geospatial domain, to define and explore highly-coordinated visualizations (Anselin et al., 2002; Butkiewicz et al., 2008; Gatalsky et al., 2004; Guo et al., 2006; Widjaja et al., 2015). Some researchers have also started to perform usability evaluations on their CMV tools (Convertino et al., 2003; Golebiowska et al., 2017; Griffin and Robinson, 2015; Plumlee and Ware, 2006).

While many of the current CMV tools have proven to be quite useful for integrating 2D/3D maps with other visualization forms to support exploratory geo-visualization, they were never designed for the purpose of exploring and comparing multiple geospatial datasets in the context of web-based virtual globe applications. Up to now, there are only a few applications that concern with coordinated use of virtual globes and other view forms. For example, to analyze multivariate climate data in the geospatial context, Zhang et al. (2013) presented an interactive, dual-domain visual analytics framework that integrates parallel coordinate plots, pie and bar charts into a Google Earth virtual-globe view. Hecher et al. (2015) developed a web-based visualization platform, termed V-MANIP, for exploring and analyzing multidimensional satellite data. In V-MANIP, there are four fixed views, including a 2D

map view, a virtual-globe view, a rectangular-box view, and a 2D visual analytics view, to show the same satellite data at the same time, and each view is synchronized with other views to display the same spatial area based on user's interaction operations. While V-MANIP has demonstrated the possibility to visualize and analyze the same geospatial dataset simultaneously in different views, it was limited by its defect relative to data sources and viewed windows because it cannot deal with multiple datasets within multiple virtual-globe views. Therefore, it is useful but could not be expanded to deal with other application scenarios when exploring and comparing multiple different geospatial datasets within multiple virtual-globe views are required. In brief, up to now, there are still no perfect methods or easy-to-handle software toolkits for the exploration and comparison of multiple geospatial datasets within coordinated virtual-globe views. Thus, it is an essential task to develop a universal method that can be applied to a wide range of multiple-view virtual-globe scenarios and can be easily adapted by the user.

In this paper, we explore the coordination technique and associated implementation methods for browsing and comparing multiple geospatial datasets in the web-based virtual globe environment. Our ultimate goal is to propose and implement a general multiple-view visualization framework for geospatial comparison, which is suitable to deal with all kinds of online virtual globes freely and flexibly. In order to achieve this goal, we first summarize the inter-relationships between multiple virtual-globe views and then construct the coordination mechanism for these views. Subsequently, the implementation program and its applications are illustrated in great detail. We also perform an informal usability evaluation with experts in both exploratory

visualization and spatial analysis. Each participant was presented with the original single-view application and our multiple-view-enhanced virtual globe application. It was clear that these everyday users of online virtual globes had all encountered the limitations of single-view virtual globes we address in this paper. Their feedback confirms that, with the help of multiple coordinated views, the presented virtual globe application makes the geospatial comparison more effective with minimum cognitive effort.

2. Visualization framework for multiple coordinated virtual-globe views

There are several technical challenges involved in designing and developing a multiple-view visualization framework for comparing and analyzing geospatial datasets in the web-based virtual globe environment. First, we need to depict what form the relationship between multiple virtual-globe views will take and then work out how users interact with multiple views to achieve that form. Concurrently we need to maintain the coordination between multiple virtual-globe views and finally work out how to show the same geospatial area simultaneously and react on users' operations without delay.

Based on the above considerations, we propose a novel visualization framework to support exploring, comparing, and analyzing geospatial datasets within multiple virtual-globe views simultaneously. As shown in Fig. 1, this visualization framework not only comprehensively considers the inter-relationships between multiple virtual globes, but also effectively handles the coordination mechanism for diverse views to respond to users' manipulations. The major issues for this framework
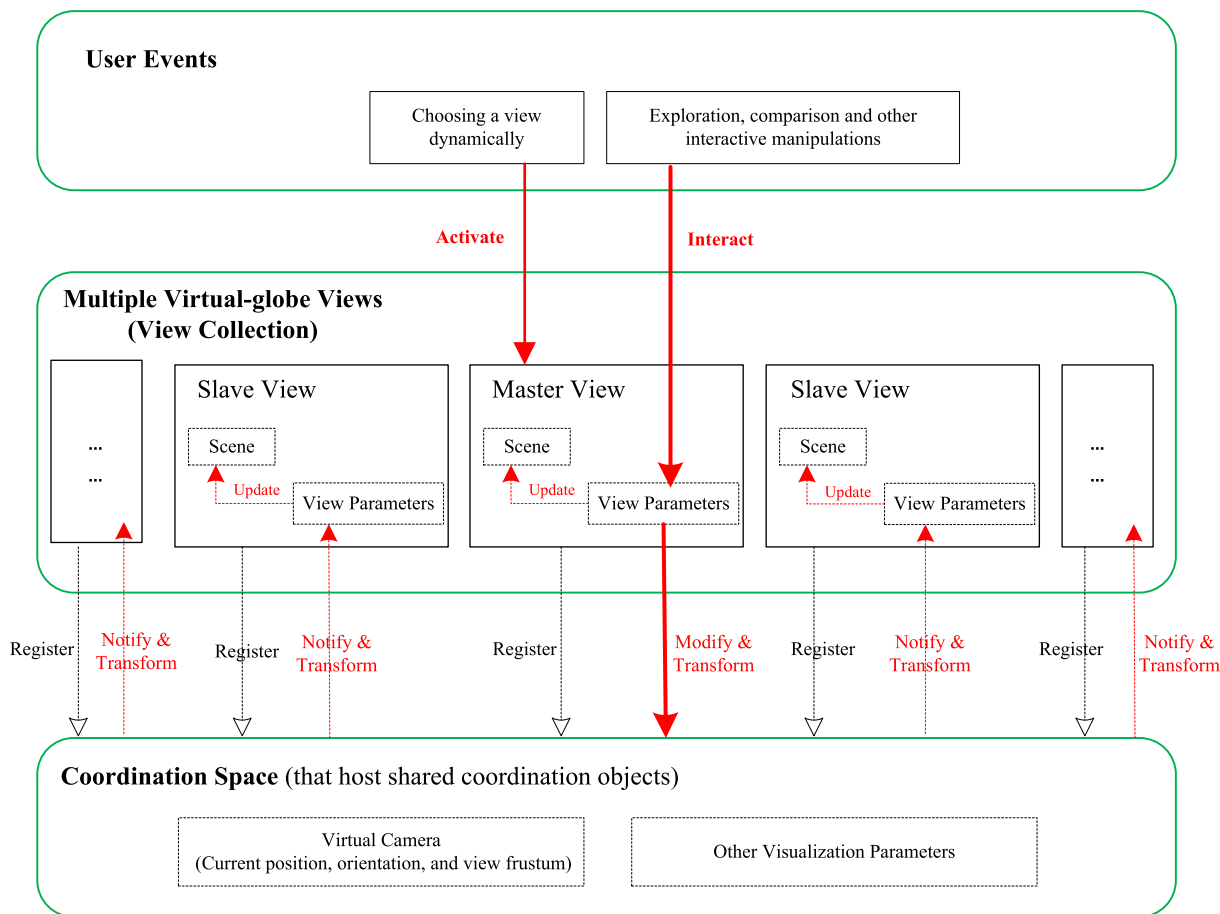

Fig. 1. Visualization framework for exploring, comparing, and analyzing geospatial datasets within multiple virtual-globe views.

involve two essential aspects: the inter-relationship between multiple virtual-globe views, and the coordination mechanism for multiple virtual-globe views.

2.1. Inter-relationships between multiple virtual-globe views

Over the years, many researchers have designed a wide variety of creative techniques, such as overview + detail (Cockburn et al., 2009), focus + context (Butkiewicz et al., 2008), master/slave (Roberts, 2007), world in miniature (Stoakley et al., 1995), small-multiples (Tufte et al., 1997) and different views (Seeling and Becks, 2004), to depict the inter-relationship between multiple coordinated views. These approaches are aimed at various application contexts and suited to different visualization forms, but none of them can be directly applied to multiple-view virtual globe applications. To express the inter-relationship between multiple virtual-globe views, we propose a dynamic master/slave strategy based on the concept of the master/slave relationship combined with the coordination mechanism through user manipulation within individual views.

The term master/slave describes the situation where one device controls one or more other devices unilaterally. It involves a master device selected from a group of eligible devices, and several other devices acting in the role of slaves (Roberts, 2007). In the context of multiple-view virtual globe control, the master/slave configuration is used for exploration process sharing purpose when multiple virtual-globe views containing different geospatial datasets are coupled to several common visualization parameters. One view is defined as the master and is configured for running in the user interaction mode, whereas the other views defined as slaves are configured for running in the passive navigation mode. As shown in Fig. 1, at a particular moment, the user can choose a view for interaction and activate it as the master acquiescently, while other views are slaves controlled by the master view. The slaves are synchronized to the master because any manipulation on the master triggers the same commands on the slaves.

In fact, the traditional master/slave configuration is only suitable for the unidirectional control of one or more slaves by a single master. Once the master/slave relationship is established, the direction of control is always from the master device to the slave devices. That is, in this situation, the roles and functions of the master and the slaves are fixed, and generally no exchange occurs at will. However, for multiple-view virtual globe applications, the roles and functionalities of the master and slave views are not fixed because they may transform at any time in order to fit user's interactions. For instance, in virtual-globe-based multiple-view visualizations, the user generally wants to select and activate a virtual-globe view at a particular moment, treating it as the master view for interaction. At this time, other virtual-globe views are slaves. While at another moment, the user may choose and activate another virtual-globe view for operation. At this point, the newly activated view becomes the master, and the previous master is downgraded to a slave automatically. These investigations hence require the roles of the master view and the slave views controlled by the master are dynamically transformable. We refer to this type of inter-relationship between multiple virtual-globe views as the dynamic master/slave relationship. In practical applications, we should dynamically set the view activated by the user to the role of the master view according to the user's choice, and thus, there is only one master view at a given time whilst the number of the slave views controlled by the master is not limited.

To implement such a relationship, a view collection, which contains an array of ordered virtual-globe view instances available for view selection, can be created. Each view in the collection contains a boolean attribute, *IsMaster*, to signify whether it is the current activated view. If the user's input (such as mouse movement or touch) activates a virtual-globe view, the *IsMaster* attribute for this view immediately becomes to *True*, setting the view to the master. At the same time, the *IsMaster* attributes for other views are set to *False* to mark them as slaves. Using

this elegant trick, we can record the roles of the master and slave views to achieve subsequent coordinated visualizations.

2.2. Coordination mechanism for multiple virtual-globe views

When users explore and compare different geospatial datasets placed in multiple virtual-globe views, the coordination across these views need to be maintained automatically so that each view displays the same geospatial area and responds to users' manipulations (such as rotating, zooming, panning, swooping, and flying to a destination) in any other view consistently and synchronously.

At present, there are certainly many different models and architectures to achieve view coordination (Roberts, 2007; Widjaja et al., 2015). While each of them has a specific abstraction level and can be used to address several particular application requirements, the shared coordination object approach (Boukhelifa et al., 2003; Boukhelifa and Rodgers, 2003) has been widely accepted by most researchers as a general but efficient strategy to construct underlying coordination in exploratory visualization (Roberts, 2007; Widjaja et al., 2015). This approach is based on views sharing several abstract objects (called coordination objects) that can be transformed into actual meaningful parameters (such as the visualization parameters of the dataflow model) for controlling the rendered view. It comprises four primary components (including basic visualization processes and states, coordination space, coordination events, as well as translation and notification functions) and some possible subsidiary elements (such as registration or constraints). This approach provides a generic view coordination architecture for information visualization because it encapsulates nearly all forms of coordination in multiple-view applications, suits to any stage of the visualization pipeline, and can be adapted by the user to solve various practical problems (Boukhelifa et al., 2003; Boukhelifa and Rodgers, 2003; Roberts, 2007). Thus, it also fits well with multiple-view virtual globes to define and implement highly-coordinated visualizations.

According to the rudiment of the shared coordination object approach (Boukhelifa et al., 2003; Boukhelifa and Rodgers, 2003), the coordination between multiple virtual-globe views could be realized by sharing a series of abstract yet common coordination objects derived from the meaningful view parameters within the actual virtual-globe views. When the user operates a particular view by explicit actions or automatically, the coordination event is immediately triggered to modify the values of one or more coordination objects. Then the shared coordination objects concurrently notify that the actual view parameters for each virtual-globe view need to be changed, updating the images of all views coincidentally.

In multiple-view virtual globe applications, the shared coordination objects can be grouped into two types: the virtual camera object, as well as other visualization parameters abstracted from virtual-globe views, depending on their functions and manipulation characteristics. The virtual camera object is abstracted from the actual camera parameters that control the scene range and level of detail within each virtual-globe view, representing the state of the camera's current position, orientation, and view frustum. Other visualization parameters contain properties for controlling imagery layers within virtual globes (such as the brightness, contrast, gamma, hue and saturation of imagery layers in each virtual-globe view), the current coordinates of user's mouse clicks, the selected geospatial objects, and other possible notions used by the views to control the coherence for all views. Taking the virtual camera object as an example, the rest of this section will explain how to maintain the coordination between multiple virtual-globe views.

The scene in a virtual-globe view is composed of the virtual world space, a 3D digital model of the Earth, a collection of geospatial objects, as well as a virtual camera used to simulate user's viewpoint in the world coordinate space. The position and state of the virtual camera determine which parts of the Earth model and which objects assembled into the Earth need to be rendered and ultimately presented to the user.

When the user explores geospatial data in the 3D virtual-globe environment, the virtual world space and its embedded Earth model are immobile, while the location and angle of the virtual camera constantly transform, thereby leading to the change of the user's visible range. In multiple-view virtual globe applications, each view possesses a virtual camera. In order to show a consistent geospatial area, it is necessary to maintain synchronization (or coordinated transformation) of individual camera status.

For multiple virtual-globe views with the dynamic master/slave relationship, there are three steps to coordinate the virtual cameras within individual views. First, the master view, which is activated by the user's operation, is elected from the available view collection, according to the value of the *IsMaster* attribute. Then, the camera parameters of the master view, such as the camera position, orientation, and view frustum, are obtained and assigned to the shared virtual camera object. Finally, the camera parameters of each slave views (whose *IsMaster* attribute is *False*) are reset to match the latest value of the shared virtual camera object, thereby realizing the sharing and synchronization of the camera parameters within multiple virtual-globe views.

In order to synchronize the scenes across multiple views naturally, it is necessary to choose an appropriate time to schedule and execute the above-mentioned coordination events, weighting and considering the computational performance consumptions and the users' experiences. Currently, there are two ways to choose the potential time for synchronization. The first is to monitor the camera state of the master view, performing the coordination events when the shared virtual camera changes; while the second is to listen to the clock of the master view, raising the coordination events when the clock changes.

In the first case, coordination events are triggered only when necessary, specifically when the camera state of the master view changes. Therefore, it requires less computational overhead and rendering costs. When using the second method, it is equivalent to perform continuous, real-time camera synchronization because the clock of the master view is always changing. Thus, it will cause more view updates and hence consume more computing resources. However, in terms of the users' experience, the second method is obviously superior to the first one. If the first method is used, the coordination events, which would change the state of the slave views, are not triggered immediately when the

user alters the actual camera parameters of the master view (such as rotating a virtual-globe model). They are triggered only when the user's action is complete. This results in that the scenes of the slave views may not transform synchronously when the user manipulates the master view. Instead, slave views will abruptly synchronize the scene with the master view only when the user suspends the operations in the master view. Obviously, this is an asynchronous coordination for multiple virtual-globe views because it may cause significant time lags. In contrast, the second method can produce a synchronous coordination, and possesses a smoother end-user experience since the scenes of the slave views are always coordinated with the changed master view. Then, after considering the trade-off between the performance consumption and the user experience, the second method is recommended to schedule and execute the coordination events for multiple-view virtual-globe applications.

Similar to the virtual camera object, other visualization parameters (such as user-selected geospatial entities or imagery layer parameters for all virtual globes) also can be synchronized through the above-described coordination mechanism.

3. Implementation

To demonstrate the effectiveness of our proposed visualization framework, MultiGlobe (http://earthbim.com/view/MultiGlobe), a web-based virtual globe application that is designed for the purpose of exploring, comparing and analyzing multiple diverse geospatial datasets within a coordinated multiple-view environment, is developed using the Cesium virtual globe (Analytical Graphics Inc., 2011) and its JavaScript library, CesiumJS (Analytical Graphics Inc., 2018b). As shown in Fig. 2, the user interface of MultiGlobe consists of two parts: (1) a view layout panel, which is designed for configuring the layout of multiple views manually, is located in the upper-left corner of the webpage; and (2) several virtual-globe views, occupying the main space of the screen, can handle mouse and touch screen inputs independently.

Using the view layout panel, users can configure the screen to display multiple virtual-globe views by choosing an expected view layout style or entering the view numbers of the horizontal and vertical directions. In addition to the virtual globe itself, each virtual-globe view comes with several accessory widgets by default, labeled in Fig. 2 and
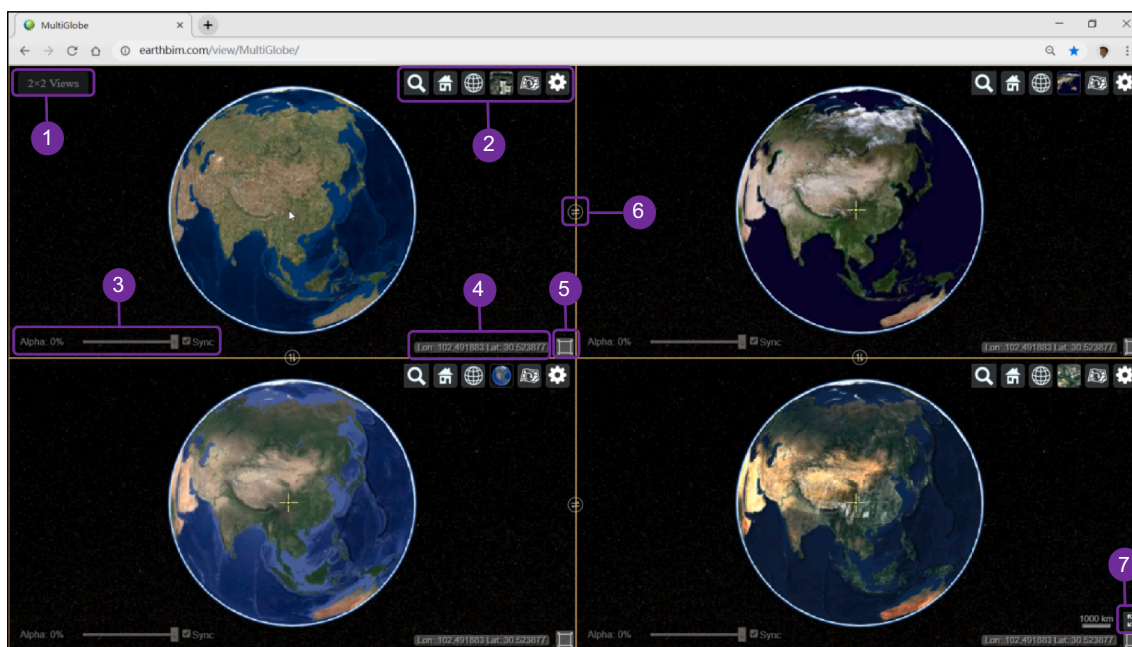

Fig. 2. User interface of MultiGlobe: (1) View layout panel; (2) Exploration widgets; (3) Transparency controls; (4) Coordinate information display; (5) Single/multiple view switcher; (6) Swap views button; and (7) Full-screen button.

divided into four groups:

(1) A set of exploration widgets, located at the upper-right of each virtual-globe view, include such buttons as "Geocoder", "Scene Mode Picker", "Base Layer Picker", "Add New Data" and "Settings". The first four are default exploration widgets embedded into the Cesium virtual globe (Analytical Graphics Inc., 2011), while the last two are newly added widgets for enhancing exploration capabilities. In particular, through the "Settings" button within each view, the user can configure the view interface to include or exclude individual widgets and other features.

(2) A horizontal slider and a checkbox, located in the bottom left of the view, are designed for controlling the transparency of the imagery or map draped over the base layer of the virtual globe in the current view. The slider specifies the value of the transparency, while the checkbox determines whether the transparency of the current view changes with other views.

(3) A group of widgets, located in the bottom right of the view, include a "Coordinate Information" bar (displays the geographic coordinates of the current mouse position), a "Single/Multiple View" switcher (determines whether to display a particular view individually or multiple views simultaneously), and a "Full Screen" button (makes the webpage full screen, valid only for the view on the lower right side of the screen).

(4) Several "Swap Views" buttons, each located between two adjacent virtual-globe views, allow users to swap the positions of these views.

By utilizing the WebGL-enabled browser (like Google Chrome, Firefox, Edge, Opera or Internet Explorer 11), users can freely access the MultiGlobe application from anywhere and at any time through the web. By default, when users open the MultiGlobe webpage, it presents a 2 × 2 view layout (2 views in horizontal and vertical directions respectively). According to their actual needs, users can easily modify the view layout, dividing the screen into a desired multiple-view style. Using the "Base Layer Picker" button within each view, users can conveniently choose appropriate imagery or terrain datasets from a set of built-in data sources to display them on the globe. Through the "Add New Data" button, users can freely load other custom imagery layers, which conform to the standard service specifications (such as OGC WMS and Esri ArcGIS MapServer), into the current view and drape them over the virtual globe's surface for subsequent exploring.

When users explore geospatial datasets within MultiGlobe, coordination between multiple virtual-globe views is automatically achieved through the shared camera object and other visualization parameters. Following the user's actions in the activated view, all the other views display the same geospatial area and react to user events consistently and synchronously. To facilitate exploration and comparison more conveniently, MultiGlobe also offers several optional function components, such as adjusting the transparency of the imagery or map, displaying geographic coordinates, switching between the single-view and multiple-view modes.

4. Applications

MultiGlobe inherits plenty of essential functions that have been implemented in the traditional single-view virtual globes, focusing on comprehensively validating the exploration, comparison, and analysis of different geospatial datasets in a coordinated multiple-view environment. It can be used in a number of fields and scenarios, from general global imagery browsing to more specific applications such as comparing digital maps and finally assessing terrain data. In this section, we present an in-depth presentation of the geospatial datasets behind the three typical application scenarios. We begin by exploring and comparing global imagery layers derived from many different providers. We then give an example of examining the dynamic time-

varying land-use and land-cover change (LUCC) datasets. Finally, we exemplify how our application is used to compare and evaluate the accuracy of DEMs with different spatial resolutions and from different data sources.

4.1. Exploring and comparing global imagery layers derived from diverse providers

MultiGlobe integrates a large variety of imagery layers released by a number of imagery providers, such as Bing Maps (Microsoft, 2005), ESRI ArcGIS Online (Esri, 2017), Google Maps (Google Inc., 2005b), Mapbox (Mapbox, 2010), Map World (NGCC, 2011) and Sentinel-2 (EOX IT Services GmbH, 2017). Although all of these imagery layers can cover the whole Earth, their acquisition date and spatial resolutions vary greatly due to different data sources. Using MultiGlobe, we can interact with the application to create multiple coordinated virtual-globe views, select several appropriate imagery layers to display, fly to an area of interest, compare these different imageries for the same region, find out the similarities and differences between them, perceive the changes of local features, and may discover insightful facts or relationships.

For instance, since 2013, the Chinese have been carrying out a large-scaled mid-ocean land reclamation project in the waters around the Woody Island, Paracel Islands in the South China Sea. This has aroused widespread concern in the world (Larson, 2015). To observe the progress of the reclamation project and the landscape changes it causes, we can use commercial satellite imageries, such as WorldView, Pléiades, and GeoEye-1, with respect to very high spatial and temporal resolutions. However, these high-resolution commercial imageries need to be purchased for use because they are not freely available to the public. This prevents us from learning about the progress and changes of the reclamation project free of charge.

A feasible alternative is to explore and examine the Woody Island from several freely available imagery layers integrated into MultiGlobe. Using the "Geocoder" widget embedded in the virtual-globe view within the MultiGlobe webpage, we first input the place name "*Woody Island, Paracel Islands*" or its geographical coordinates (*16.836272°N, 112.336882°E*), and then the scene of each view automatically flies to the Woody Island, and finally each view presents a freely available imagery layer. As shown in Fig. 3, we choose four imagery providers (ESRI ArcGIS Online, Map World, Google Maps, and Sentinel-2, respectively) for viewing. The reason why these providers are selected is that after comparison, these imageries are highly representative in terms of image capturing time and spatial resolution. Therefore, they can reflect the overall expansion process caused by the reclamation project near the Woody Island.

From Fig. 3(A)–(D), it is easy to detect any significant changes for the land cover of the Woody Island, especially in the northeast and southwest of the island. According to the spatial distribution and changing trend of the changed features, we can determine that the order of the imagery acquisition date is: Fig. 3(A), Fig. 3(B), Fig. 3(C), and Fig. 3(D), in chronological order. In particular, Fig. 3(C) is derived from Google Maps. Using the Google Earth desktop application, we can find out that the imagery was taken on 2016/04/26. From this, we can deduce the approximate time for the other three imageries: Fig. 3(A), derived from ESRI ArcGIS Online, should be taken before launching the reclamation project in 2013; Fig. 3(B), derived from Map World, may be taken in 2013–2016 since the reclamation project was still in process; and Fig. 3(D), derived from Sentinel-2, must be taken later than Fig. 3(C) (2016/04/26), because the roads and green belts have been formed (similar to those in Fig. 3(C)), but several new features are presented in this imagery.

Although Fig. 3(D) (the Sentinel-2 imagery) ensures the currency of geospatial data by providing the latest remote sensing imagery, it also has obvious deficiencies. As shown in Fig. 4, when zooming in the imageries on the small areas, we find that the local features in the

Fig. 3. Exploring the land reclamation project in the Woody Island, and comparing imagery layers released by several freely available imagery providers, including ESRI ArcGIS Online (A), Map World (B), Google Maps (C) and Sentinel-2 (D). All imageries show the same locality near the Woody Island. Yellow rectangles in the northeast and southwest of the island indicate the locations with significant differences caused by the reclamation project. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Sentinel-2 imagery become very blurred. Thus its spatial resolution is far less than that of the other three imagery providers. In fact, due to the limitation of imaging capability, the spatial resolution of the Sentinel-2 imagery only falls between 10 and 60 m (EOX IT Services GmbH, 2017). Therefore, its imaging definition is naturally inferior to that of the ESRI ArcGIS Online, Map World, or Google Maps imagery, which generally possesses a spatial resolution of 1 m in the Woody Island.

In short, the free and open remote-sensing imageries derived from diverse providers usually have considerable differences in the acquisition date and spatial resolution. Such differences could be exploited by

users to explore and compare particular geospatial areas within a coordinated multiple-view environment, which often produces similar results that can be obtained by using high-resolution commercial imagery for a fee.

4.2. Examining and analyzing time-dynamic LUCC datasets

Shanghai is one of the four municipalities under the jurisdiction of the Central Government of China, with a residential population of over 25 million and a land area of approximately 6,700 km^2. In the past

Fig. 4. Viewing local features when zooming in the imagery of the Woody Island. Each view shows the same locality, but the spatial resolution of the Sentinel–2 imagery (D) is evidently inferior to that of ESRI ArcGIS Online (A), Map World (B) or Google Maps (C).
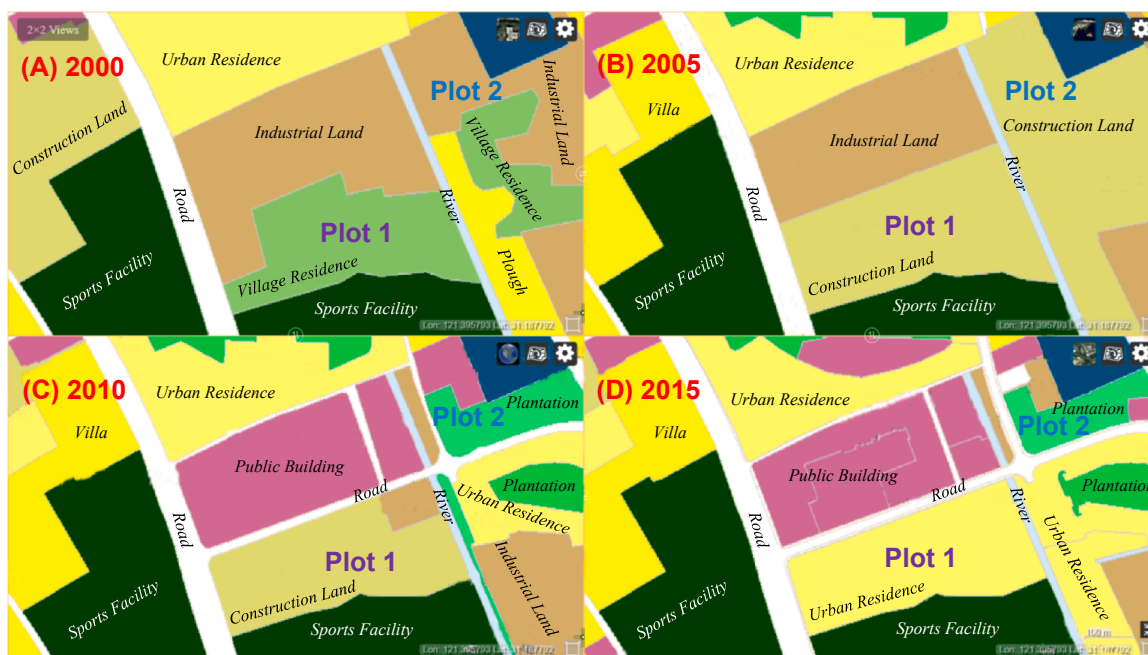
Fig. 5. Examining and analyzing time-varying LUCC datasets in Shanghai, China. Figures comparing land use category in 2000 (A), 2005 (B), 2010 (C), and 2015 (D). Each view shows the same locality.

20 years, with the accelerating urbanization process, the area of the build-up district has been continuously expanded. Thus the land cover category in Shanghai has also undergone dramatic changes. To record such changes, we produce four land cover maps for the four years, 2000, 2005, 2010 and 2015, respectively, using high-resolution aerial imageries of Shanghai from 2000 to 2015. These LUCC datasets are hosted in an ArcGIS map server to provide a unified interface to make them accessible to the general public. Using the "Add New Data" button, we can load these datasets into the MultiGlobe application to freely view and examine the dynamic changes of an arbitrary plot in Shanghai from 2000 to 2015.

Fig. 5 presents a portion of the LUCC datasets over Shanghai and shows a scenario of exploring and comparing. It can be seen from the figures that, between 2000 and 2015, there are many obvious changes in the land use category for many plots. For example, Plot 1 was first transformed from "*Village Residence*" (2000, Fig. 5(A)) to "*Construction Land*" (2005, Fig. 5(B)), and then converted into "*Urban Residence*" (2015, Fig. 5(D)); Plot 2 was first changed from "*Industrial Land*" (2000, Fig. 5(A)) to "*Construction Land*" (2005, Fig. 5(B)), and then to "*Plantation*" (2010, Fig. 5(C)).

By utilizing this time-varying dataset driven approach to compare digital LUCC maps, we can show that the land use category in Shanghai is far from static, and many plots are often in a constant state of change. In fact, MultiGlobe can act as an efficient tool to analyze the driving forces and trends of LUCC in Shanghai, as well as an intuitive platform in educating the general public about the impact of ongoing human activities on LUCC.

4.3. Comparing and evaluating the accuracy of different DEMs

As well as exploring and investigating differences in multiple imagery layers or digital maps, MultiGlobe can be used to compare and evaluate multiple digital elevation models (DEMs) with different resolutions and from different data sources. By rendering different DEMs in a coordinated 3D multiple-view environment, each subtle nuance of the DEMs can be displayed with an intuitive and vivid way, thus helping domain scientists working on generating, maintaining or exploiting such datasets to find the most appropriate DEM dataset suited

to their aims, research scales, and accuracy requirements.

MultiGlobe supports a wide variety of standard terrain formats and freely available global/local terrain servers. At present, it integrates three commonly used global terrain datasets: VR-TheWorld Terrain (VT MAK, 2010), STK World Terrain (Analytical Graphics Inc., 2015b), and Cesium World Terrain (Analytical Graphics Inc., 2018a). These datasets, generally derived from different data sources with various levels of detail, vary greatly in data format and spatial resolution. Specifically, VR-TheWorld Terrain, a terrain tileset that produces terrain geometry by tessellating height maps retrieved from a VT MÄK VR-TheWorld server, is based on the CGIAR SRTM3 dataset (CGIAR-CSI, 2008), containing global coverage with an approximate resolution of 90 by 90 m, and adopting the Height Map terrain format (height-map-1.0) to structure terrain information (Analytical Graphics Inc., 2015a). STK World Terrain, a high-resolution worldwide terrain tileset hosted in an STK Terrain server, uses the Quantized Mesh format (quantized-mesh-1.0) to encode terrain meshes (Analytical Graphics Inc., 2013). It includes elevation data from the GTOPO30 1000-meter (Entire Earth), CGIAR SRTM3 90-meter (60°N, 60°S), USGS SRTM1 30-meter (60°N, 60°S), EU-DEM 30-meter (Europe), and NED 10-meter (United States) resolution DEM data (Analytical Graphics Inc., 2015c). Cesium World Terrain is a newly released high-resolution global terrain tileset hosted by the Cesium ion platform (Amato, 2018). Similar to STK World Terrain, it is served in the Quantized Mesh terrain format, but it incorporates higher resolution elevation data in several areas that previously only have 30–90 m resolution in STK World Terrain (Analytical Graphics Inc., 2018a). For example, in England the terrain quality is upgraded to 1–2 m resolution from 30 m (Chow, 2018); and in the United States, it has improved from 10-meter resolution to 0.5–1 m (Fili, 2018). Therefore, compared with VR-TheWorld Terrain and STK World Terrain, Cesium World Terrain may bring better visual quality, more precise measurements, and more efficient spatial analysis.

Fig. 6(A) - (C) show screenshots of the above-mentioned terrain datasets that have been integrated into the MultiGlobe application. They all render a partial model of the White Cliffs of Dover, one of England's most recognizable natural landmarks that formed by 350 feet (110 m) high chalk cliffs facing the narrowest portion of the English Channel. As illustrated in Fig. 6, although draped with the same
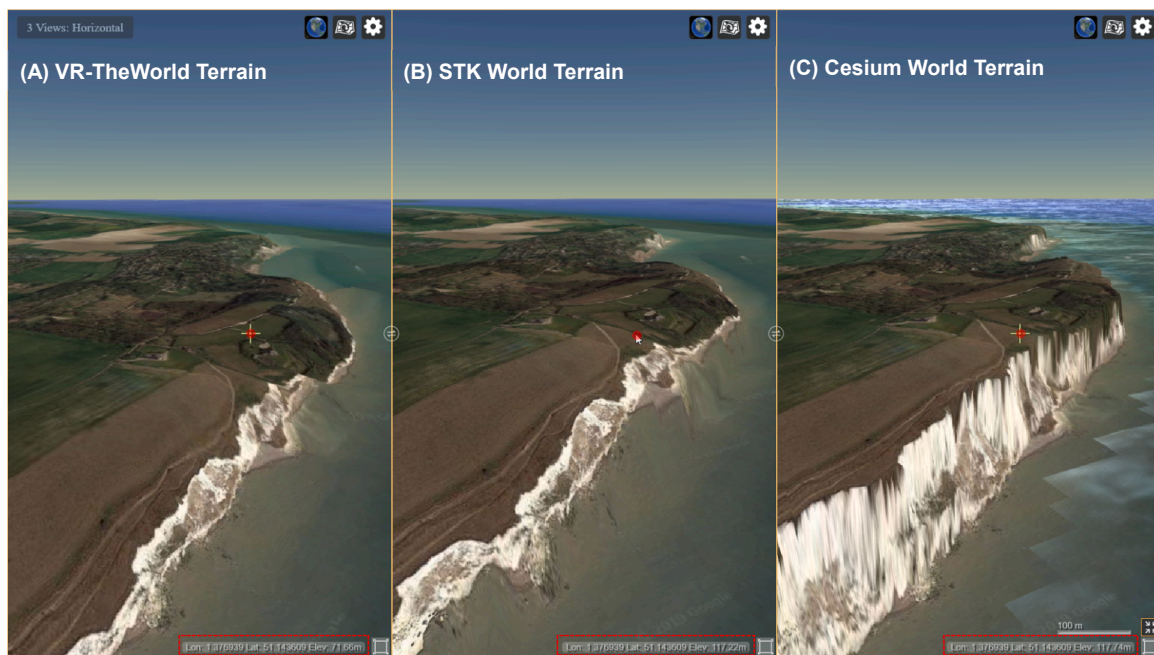
Fig. 6. Rendering of three DEMs for the White Cliffs of Dover, UK. Figures comparing visualizations of terrain datasets from VR-TheWorld Terrain (A), STK World Terrain (B), and Cesium World Terrain (C). These models vary greatly in spatial forms and elevation accuracy. Red dots are reference marks that are in the same three locations in all images to facilitate comparison, while red rectangles located in the bottom right of each view indicate the geographic coordinates of the reference points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

imagery layer (the Google Maps imagery), these three models still have tremendous differences in spatial geometry and accuracy. In the model Fig. 6(A) derived from VR-TheWorld Terrain, the cliff face appears to be very low in height, with small dips and subdued topography. So it cannot reflect the actual forms of the White Cliffs. The model Fig. 6(B) is built from STK World Terrain. In this model, the cliff face looks taller and steeper than it in the model Fig. 6(A), but it still has a relatively gentle slope, especially at the top area of the cliff. This still does not match the actual terrain of the White Cliffs. In addition, this model does not precisely match the remote sensing imagery draped over it, especially at the cliff's top and the bottom area covered by the water. In the model Fig. 6(C) derived from Cesium World Terrain, the sheer nature of the cliff face becomes apparent with the spectacular, steep feature, and the cliff's top presents a flatter surface. This model accurately captures the peaks and roughness of the surface, better corresponds to the imagery layer and thus is consistent with the actual terrain.

Moreover, by picking up the elevation value of the same locality within the models, it is found that the elevation in the model Fig. 6(A) is significantly different from the actual value (for example, at the position marked by the red dot, it is about 45 m lower than the actual value), while models Fig. 6(B) and (C) differ little from the actual value.

The wireframe views presented in Fig. 7 highlight more details of the terrain models. As illustrated in Fig. 7, the order of the density of the terrain meshes is: Fig. 7(A), Fig. 7(C), and Fig. 7(B), sorted from dense to sparse. The terrain meshes in the model Fig. 7(A) are denser than the models Fig. 7(B) and (C). However, the raw terrain data for this model is extremely sparse because the sample interval of the CGIAR SRTM3 dataset is 90 m approximately (CGIAR-CSI, 2008). This leads to a rough model with the lowest accuracy. The model Fig. 7(B) has the sparsest meshes, but it is built from the USGS SRTM1 data with 30-meter resolution (Analytical Graphics Inc., 2015c). So it is more accurate than the model Fig. 7(A). Furthermore, in the model Fig. 7(C), the spatial resolution of the raw data is upgraded to 1 m (Analytical Graphics Inc., 2018a). Therefore, although the mesh density of this model is not as dense as that of model Fig. 7(A), it can produce the most accurate, reasonable terrain to represent the surface's curvature with a compelling visualization.

Thus, for the quality perspective, in the region of the White Cliffs of Dover, the DEM derived from Cesium World Terrain has the highest accuracy of all of the three models, followed by STK World Terrain, which has credible values in elevation data, but lacks reasonable shapes of terrain features like cliffs and hills. Comparatively, the model derived from VR-TheWorld Terrain has the worst accuracy. More importantly, we also can see that the DEM built from Cesium World Terrain is better matches the imagery layer than any others. This intuitively demonstrates the advantages of fusing high-resolution data sources into producing high-precision DEMs.

5. Usability evaluation

In March 2019, we released the first version of our multiple-view-enhanced application, MultiGlobe, and performed an informal evaluation to solicit feedback on the usefulness of the interface thereof. Each of the three scenarios described in Section 4 was presented first in the original single-view virtual globe (Cesium) for exploring and comparing, and then with the MultiGlobe application to two groups of audiences from the geography department at East China Normal University. Each group consisted of 15 participants, all of whom were a mixture of faculty members and graduate students engaged in geography research and spatial analysis. These participants all had previous experience in exploratory visualization and working with virtual globe applications.

From the feedback we have gathered, all participants were free to use any of the available virtual globe applications, and they did not encounter many difficulties whether using the single-view Cesium or the multiple-view MultiGlobe. However, many participants admitted the inevitable issue of the loss of spatial awareness when using the single-view virtual globe to browse and compare multiple different geospatial datasets. This is the same problem they had previously encountered in their work when they utilized other virtual globe applications. They believed that using MultiGlobe is a good solution to this problem, in that "it organizes and displays multiple virtual-globe views in a screen with an orderly coordinated manner, so it really does help a lot to discover and understand the differences between geospatial
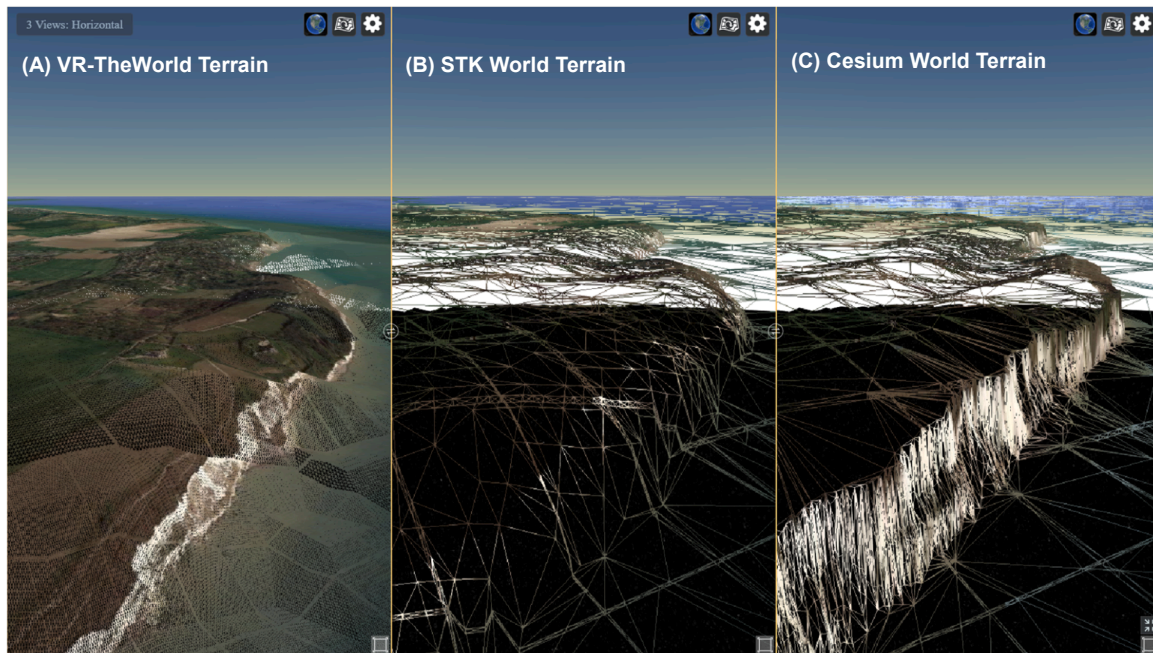
Fig. 7. Wireframe visualizations of terrain models derived from VR-TheWorld Terrain (A), STK World Terrain (B), and Cesium World Terrain (C).

objects", and that "you can freely create multiple views, arrange these views in the screen, and specify the contents of each view; thus it allows you to navigate and compare more fluidly between different views or datasets".

All participants felt comfortable with the user interface of MultiGlobe as it provides comprehensive yet intuitive functions. The ability of comparing geospatial datasets within multiple coordinated virtual-globe views was also identified as attractive, with one participant specifically commenting that "having such capability in virtual globe applications would make it much easier to quickly and visually detect changes of geospatial features, to find out outliers between multiple datasets, and to draw out their correlations or disparities. Now I can start to view and compare different datasets at one time without having to launch multiple virtual globe applications and then opening up multiple geospatial datasets. It would significantly reduce the time cost for the comparison and the discovery of multiple geospatial datasets."

In MultiGlobe, the user can interact with geospatial datasets in various modes. Particularly, we provide the ability to switch between the single-view and the multiple-view modes. Users can switch to a single-view window by clicking on the "Single/Multiple View" switcher located in the lower right corner of each view. By preserving the single-view mode, we ensure that users always experience the existing capabilities and functionality of the current single-view virtual globe applications. By using the multiple-view mode, the same geospatial areas within multiple views can now be simultaneously explored and directly compared on the screen, alongside each view that can be optionally displayed as exclusive on the screen. This reduces the navigation required to switch between multiple virtual globe applications, and thus achieves the maximum spatial awareness. All participants appreciated the independence of individual displays and the coordination between multiple views allowing them to freely choose desired visualization mode as their will, with one noted that "the single-view mode can be used for global browsing, while the multiple-view mode is suitable for local comparison."

MultiGlobe enables users to dynamically select a view from a set of eligible views to act as the master view. It also synchronously renders the focus positions both in the master and the slave views. More importantly, all operations can be coordinated between these views. One

participant elaborated that "using MultiGlobe eliminates the burden of having to switch windows and manually focus to the destination to inspect different imageries, maps or terrain data at the same locality. This drastically reduces cognitive memory requirements, speeds up the comparison process, increases the relevance and accuracy of geospatial comparison, and finally facilitates the understanding of geospatial changes."

After having experienced such applications, most of the participants indicated their belief that MultiGlobe was a powerful tool for interacting with multiple virtual-globe views when performing exploratory visualization tasks. They were delighted to exploit this tool to explore and compare their own existing geospatial data either in course learning or scientific research. Many participants even hoped to be able to incorporate more visual analysis and interaction functions into the next version of MultiGlobe to improve its geospatial analysis capabilities and competitiveness.

6. Conclusion and future work

Existing single-view virtual globes have serious limitations when dealing with multiple different geospatial datasets for a specific region or theme with multi-source, multi-resolution, or multi-temporal features. In this paper, we have designed a general visualization framework that enables exploring and comparing multiple datasets with coordinated multiple views in the web-based virtual globe environment. This framework can be used to replace or supplement the fixed single-view interfaces of traditional virtual globe applications. We have developed a prototype application, MultiGlobe, as the reference implementation of this framework, and demonstrated the effectiveness and applicability of the multiple-view interface by presenting three typical application scenarios. In each case, we can see the common benefits gained by migrating to multiple-view virtual globes from the traditional single-view interfaces. Our informal evaluation with experts in exploratory visualization and spatial analysis confirms that with the enhancement of multiple coordinated virtual-globe views, exploring and comparing different geospatial datasets become more comfortable and intuitive. The most significant feature of our work is that it contextualizes multiple geospatial datasets in a coordinated multiple-view environment, making it possible to simultaneously capture and

compare similarities and differences of multiple complex datasets. It would reduce the loss of cognitive ability when users switch from one dataset to another, enabling them to browse data, compare differences, develop hypotheses, and derive answers more quickly and efficiently.

The most attractive application occasions of the presented visualization framework and associated implementation involve large projected screens and tiled displays in the clustered rendering environment. Along with the increase of very large displays, dual-screen computers, and foldable smartphones, users are wishing to coordinate multiple smaller views working together to form larger visualization, thus we hope that our visualization framework and its future extensions will be widely used in a variety of geospatial visualizations to empower users with the ability to explore and compare multiple different datasets across the same region. As future work, we will fuse more data sources (including online imageries, maps, terrain datasets, and other freely available geospatial data) into MultiGlobe to make it easier for users to navigate and compare more global/local geospatial information. We will further integrate GIS analytical tools to assist users in geoscientific analysis, guiding the main focus of the current applications no longer limited to information visualization. In addition, although our work has been done using the Cesium virtual globe, our visualization framework can easily scale to support other online virtual globe platforms and associated applications. We also aim to reconfigure the user interface of the MultiGlobe application to be applied to other virtual globes, and even to integrate multiple different virtual globe platforms into a unified interface to achieve coordinated navigation and comparison.

Acknowledgments

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