Front. Earth Sci. 2014, 8(4): 524–539
DOI 10.1007/s11707-014-0438-7

RESEARCH ARTICLE

SolidEarth: a new Digital Earth system for the modeling and visualization of the whole Earth space

Liangfeng ZHU (✉)[1], Jianzhong SUN[2], Changling LI[3], Bing ZHANG[1,4]

1 Key Laboratory of Geographic Information Science for Ministry of Education, East China Normal University, Shanghai 200241, China.
2 Center for Earth System Science, Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201203, China.
3 School of Environmental Science and Spatial Informatics, China University of Mining and Technology, Xuzhou 221008, China.
4 College of Geomatics Engineering, Nanjing University of Technology, Nanjing 211816, China.

Abstract Although many of the first-generation Digital Earth systems have proven to be quite useful for the modeling and visualization of geospatial objects relevant to the Earth's surface and near-surface, they were not designed for the purpose of modeling and application in geological or atmospheric space. There is a pressing need for a new Digital Earth system that can process geospatial information with full dimensionality. In this paper, we present a new Digital Earth system, termed SolidEarth, as an alternative virtual globe for the modeling and visualization of the whole Earth space including its surface, interior, and exterior space. SolidEarth consists of four functional components: modeling in geographical space, modeling in geological space, modeling in atmospheric space, and, integrated visualization and analysis. SolidEarth has a comprehensive treatment to the third spatial dimension and a series of sophisticated 3D spatial analysis functions. Therefore, it is well-suited to the volumetric representation and visual analysis of the inner/outer spheres in Earth space. SolidEarth can be used in a number of fields such as geoscience research and education, the construction of Digital Earth applications, and other professional practices of Earth science.

Keywords Digital Earth, Earth space, full dimensionality, visualization

1 Introduction

In January 1998, the idea of a Digital Earth was first formally proposed by former US vice-president Al Gore at the California Science Center, and a vision of Digital Earth as a computer-based, multi-resolution, and three-dimensional (3D) representation of the entire Earth was also articulated (Gore, 1999). Since then, impressive progress has been made in basic theories, implementation techniques, and building applications of Digital Earth all over the world. To support the development of the Digital Earth, a series of sophisticated and powerful virtual globes, such as Google Earth, NASA's WorldWind, Microsoft's Bing Maps, ESRI's ArcGIS Explorer, Wuhan University's GeoGlobe, the Chinese Academy of Sciences Digital Earth Prototype System, Unidata's Integrated Data Viewer, Digitnext's VirtualGeo, and other free geo-browsers (Goodchild et al., 2012), have been created, that have subsequently evoked world-wide interest and entered the public consciousness (Butler, 2006; Craglia et al., 2008; Bailey and Chen, 2011; Guo, 2012). As the representatives of the first-generation Digital Earth system, these virtual globes not only offer users the capability to image, analyze, synthesize, model, and interpret geospatial objects and spatial phenomena on different spatial aggregation, but also possess the ability to enhance science by providing reliable platforms for exploring, discovering, analyzing, exchanging, and sharing geospatial information in scientific research and pedagogy (Butler, 2006; de Paor and Whitmeyer, 2011; Martínez-Graña et al., 2013; Wang et al., 2013). Nowadays, Digital Earth systems are important and everyday tools used by scientists, educators, government officials, and the general public to conduct research, exchange ideas, and share knowledge with a global perspective in a natural and intuitive way (Yang et al., 2010; Guo, 2012; Yu and Gong, 2012; Zhu et al., 2014).

The first-generation Digital Earth systems, such as the Google Earth virtual globe, focus on the access, display, analysis, and service of geospatial information relevant to the Earth's surface and near-surface (Butler, 2006; Craglia et al., 2008, 2012). They can help users to process data with better resolution and to extract information existing in geographical space. Therefore, they are particularly useful

Received August 29, 2013; accepted December 30, 2013

E-mail: lfzhu@geo.ecnu.edu.cn

for geography that regards geographical entities as research objects. While the first-generation Digital Earth systems have the potential to extend to nearly all fields of the Earth sciences, the use of these existing virtual globes in some specific Earth science subjects (such as oceanography, atmospheric science, geology, and geophysics) and multi-disciplinary research has encountered some impediments. Several experiments have highlighted a number of shortcomings and some serious limitations when using these existing virtual globes (Bernardin et al., 2011; de Paor and Whitmeyer, 2011; Goodchild, 2012). Two critical problems that scientists may encounter when trying to use the first-generation Digital Earth systems are listed below.

One problem with existing Digital Earth software systems is their inability to represent the whole Earth space in 3D comprehensively and clearly. Current virtual globes are based on a space division of the Earth's surface, which is tiled seamlessly by a series of grids with different scales and can be subdivided into arbitrarily fine grids (Gore, 1999; Butler, 2006; Goodchild, 2008; Bernardin et al., 2011). Users can import geospatial data, like maps, images, and 3D ground object models, and drape them over the corresponding underlying grids. Essentially, this subdivision scheme is a 2D/2.5D division because the space division only relates to the surface of the Earth, and has nothing to do with the third spatial dimension extending above and below the Earth's surface. Although this global representation is ideally suited for the modeling, visualization, and analysis of geospatial objects existing in geographical space, it is limited by its defect relative to spatial dimensions because it cannot represent the above-ground and underground space of the Earth. Thus, it is not appropriate in cases where real-3D modeling and analysis of geospatial objects/phenomena/processes within atmospheric and geological space are required.

A second problem is that most current Digital Earth systems generally lack necessary advanced functions in 3D visualization and spatial analysis for geospatial objects. The first-generation Digital Earth systems were designed for the purpose of modeling, visualizing, and analyzing geographic objects that can be draped over the solid Earth terrain model (de Paor and Whitmeyer, 2011). Using elegant engineering (such as multi-scale representation, self-adaptive visualization, progressive transmission, and clever server-side data caching techniques), current virtual globes can effectively transmit and vividly visualize some specific geospatial data, like 2D vector maps, 2D raster images, 2.5D digital elevation models, and 3D vector models, over the Internet (Butler, 2006; Craglia et al., 2008). However, they are not able to offer existing tools or built-in functions to transmit, render, and visualize 3D volumetric data automatically and seamlessly, especially when the data sets are in large volume. High-quality volume visualization is important and particularly useful to Earth scientists of all disciplines since the volumetric data is widely used in the modeling and analysis of the physical, chemical, and other properties within atmospheric and geological space. More importantly, the first-generation Digital Earth systems cannot provide professional volumetric/structural analytic tools to support true 3D scientific analysis directly on 3D volumetric models (Shen et al., 2013). Thus, it is either hard or impossible to visualize and analyze the spatial and temporal relationships/correlations between geographical, geological, and atmospheric objects.

With the implementation of a variety of global earth observation programs, especially Earth deep exploration programs since the 1970s, scientists began to conveniently gather large quantities of geospatial data to imagine the three-dimensional structure and composition of the Earth (Dong et al., 2011). Nowadays, the scope of human cognition and activity has been extended to the entire Earth space including the Earth's subsurface and atmosphere, as well as the Earth's surface. There are increasing demands for an integrated system for interpreting, modeling, visualizing, and analyzing the interior and exterior space of the entire Earth. However, current Digital Earth systems have limitations when used for mapping and modeling geological and atmospheric features. The increasing pressure to achieve a comprehensive and complete understanding of the whole Earth space has created a need to extend the first-generation Digital Earth system into a next-generation system that can process 3D geospatial entities and geo-phenomena with coherent representation, management, modeling, visualization, analysis, and application of information. It is an essential task to develop a new Digital Earth system with full spatial dimensionality and efficient geospatial analysis functions.

To keep up with such scientific demands, we designed and developed a new Digital Earth application, termed SolidEarth, to overcome the above-mentioned limitations. SolidEarth integrates visualization and analysis methods of high-resolution data, like images, DEMs, 3D vector models, and 3D volumetric models, over large spatial extents with global GIS techniques. SolidEarth is a new Digital Earth system that allows the visualization and analysis of the exterior/interior space of the Earth at different levels. The Digital Earth system offers users the exclusive capacity to model, visualize, locate, navigate, and analyze the exterior and interior space of the Earth. It could dramatically improve the efficiency of the first-generation Digital Earth system, and can be widely used in a number of fields such as geo-scientific research and education, construction of Digital Earth application systems, and other professional practices of Earth science.

2 System objectives

The development of SolidEarth is driven by huge interest and need on the part of relevant disciplines like geology, geophysics, meteorology, and oceanography (Bailey and

Chen, 2011; de Paor and Whitmeyer, 2011; Dong et al., 2011; Yu et al., 2012). Compared to previous Digital Earth systems, the most important feature of SolidEarth is that it provides more abundant, sophisticated, powerful, and professional functions, specialized as required by geoscience researchers. More specifically, SolidEarth must support the following:

1) Reconstruction and visualization of 3D structure models that give the boundaries between the different defined earth spheres and 3D property models for the spatial distribution of the physical, chemical, and other properties within the exterior and interior space of the Earth.

2) Spatial analysis of geometrical structures and property parameters of geological objects hidden beneath the Earth's surface. It should provide users with a series of true 3D analytic tools, such as searching, querying, freely roaming, and arbitrary incision directly on 3D solid models.

3) Multi-resolution representation, fast network transmission, and self-adaptive visualization of large-scaled 3D geospatial information, which mainly consists of 3D volumetric data, on the Internet.

To keep up with the above demands, we designed and developed SolidEarth cooperating with the SinoProbe Group (Dong et al., 2011), aiming to establish a new Digital Earth system for the integrative representation, modeling, visualization, and analysis of the whole Earth space. In this system, SolidEarth should not only provide computer models to reflect the actual conditions of earth spheres, but also provide a specialized scientific platform to enable studies, communication, and display of earth sciences and relevant applications. More importantly, through modeling, visualization, and analysis of geospatial data from a variety of global earth observation programs, SolidEarth should work to promote the socialization and popularization of scientific advancements in explorations of the Earth's space, especially the Earth's deep interior.

These objectives are implemented within the four components that are discussed in the following sections. First, a novel geospatial data model is developed to describe and represent multi-source geospatial information with full dimensionality. Second, the general modeling procedures for the reconstruction of 3D structure and property models in the Earth space are presented, respectively. Third, a web-based data transmission and visualization framework is proposed. And finally, a prototype system is developed to implement these functions.

3 The Earth space and geospatial data model

3.1 Structure and composition of the Earth space

In 3D space, Earth has the distinct feature of sphere structure (Fowler, 2005). With the Earth's surface as a boundary, Earth space is divided into two parts, one is the outer sphere and the other is inner. Both of those two parts have significant differences in structures and properties, as well as processes occurring in their space. The outer sphere, also termed atmospheric space, extends from the Earth's surface to the Karman line, with approximate thickness of 100 kilometers. The inner space, also termed geological space, refers to the solid portion beneath the Earth's surface. Especially, in order to highlight the significance of the surface and near-surface space, geoscientists often extract the Earth's surface and near-surface from the border between the outer and the inner spheres, and investigate it as geographical space. Therefore, the Earth's space is loosely comprisedsof three subspaces from the top to the bottom, the atmospheric space, the geographical space, and the geological space. Each subspace has different extent, characteristics, objects, as well as geospatial data and dimensionality features.

Atmospheric space is the research field of atmospheric science. Geography mainly focuses on spatial entities/phenomena existing in geographical space, as well as the human, social, and economic information. Geology and geophysics are concerned with geological objects/phenomena within geological space. Geographical space is intersected with atmospheric and geological space, and the endogenous and exogenous relief-forming processes that are simultaneously acting on the Earth's surface. Therefore, those three subspaces are not quite distinct from each other. With the steadily expanding research spectrums of a variety of sub-disciplines in Earth sciences, the requirement of an integrated and comprehensive research on whole Earth space tends to be more and more urgent. Therefore, it is necessary to find appropriate geospatial data models to coherently represent all kinds of geospatial objects.

3.2 Geospatial data model

A spatial data model is a mathematical construct for abstracting, classifying, describing, and expressing real spatial objects/phenomena as data (Jones, 1989; Wu, 2004; Wu and Xu, 2004; Zhang et al., 2009). Current spatial data models used to store geospatial data in GIS can be divided into three major categories: 2D data models, 2.5D data models, and 3D data models.

2D data models are also classified into three different types: 2D vector data models, 2D raster data models, and 2D hybrid data models. 2.5D data models, supplemented with a z-value reflecting the elevation for each pair of 2D coordinates (x, y), are mainly used for constructing digital elevation models (DEMs). 3D data models can be classified into four major subclasses as volumetric models, vector models, mixed models, and integrated models, and there are several representational models for each subclass (Wu, 2004; Wu and Xu, 2004; Turner, 2006). 3D volumetric data models, which are based on spatial partition, represent a spatial object as a combination of primitive volumes (de Floriani and Falcidieno, 1988; Wu, 2004). The conventional 3D volumetric data models include constructive solid geometry (CSG), 3D-raster, octree, tetrahedral network (TEN), tri-prism (TP), generalized tri-prism (GTP), Geocellular, etc. 3D vector data models, which describe solid volumes in terms of their enclosing surfaces, emphasize surface representation for spatial objects (de Floriani and Falcidieno, 1988; Wu, 2004). The conventional 3D vector data models include boundary representation (BRep), wire framework, and non-uniform rational B-splines (NURBS). 3D mixed data models use two or more vector/volumetric data models to describe one spatial object at the same time. These models take advantage of vector data models, for fast visualization, and of volumetric data models, for efficient spatial analysis, and well adapt to different modeling requirements derived from various background conditions and spatial resolutions (Wu, 2004). The conventional 3D mixed data models include BRep-CSG, GTP-TEN, and BRep-GTP-TEN. 3D integrated data models first apply various single data models to describe different types of spatial objects, respectively, and then integrate them into a unified 3D space to fully represent multiple types of spatial objects. The conventional 3D integrated data models include CSG + TIN + GTP, BRep + TIN + GTP, and object-oriented data models.

In terms of practicality, each of these spatial data models has both advantages and disadvantages in several aspects, such as geometric representation of geospatial objects or phenomena, space partition, topological description, and consistency maintenance (Wu, 2004). At the present time, due to the difference in their adaptabilities, none of the existing data models can faultlessly represent all or most of the geospatial objects in question. In addition, since there are tremendous differences in data acquisition methods, morphological features, modeling approaches, and applied targets between different geospatial objects and geo-phenomena, each of the existing data models can only successfully deal with certain geospatial objects in a particular range of research fields or spatial dimensionality. Therefore, to update Digital Earth applications, it is necessary to develop integrated geospatial data models and associated data structures, that apply various single data models to describe and model different geospatial objects. Using the concept of integral modeling, all of the established models can be integrated into a 3D virtual globe environment based on a unifying geospatial coordinate system, which finally leads to the full representation of the entire Earth space and geospatial objects.

Currently, it is quite possible to integrate 2D and 2.5D data models into first-generation Digital Earth systems. However, there are still no perfect methods or easy-to-handle software systems that support 3D geospatial data models completely. Several shortcomings are magnified when using the existing Digital Earth systems to represent 3D geospatial objects. One of the most outstanding problems is that the current Digital Earth systems only support 3D geospatial objects expressed by 3D vector data models like wire framework and BRep. That is, they cannot directly support 3D geospatial objects that are expressed by 3D volumetric data models. Using 3D vector data models, it is convenient to construct, update and visualize such models as natural/man-made ground objects, geologic bodies/structures, and geometric structures of atmosphere, and the amount of data to be transferred and visualized is much smaller than using volumetric data models. However, it is either hard or impossible to do 3D geospatial analysis since 3D vector data models lack the description of the real-3D topological relationships between different geospatial objects. In addition, 3D vector data models are unable to subdivide the geological and atmospheric spaces with arbitrary spatial extent into a series of small subspaces perfectly and seamlessly. 3D volumetric data models are ideally suited for describing and subdividing continuous Earth space with the feature of gradual changing, and they are suitable for various spatial operations and geospatial analysis. However, a number of complex improvements and optimizations for visualization algorithms need to be conducted to make up for such blemishes as large data size, slow computing speed, and the inefficient network transmission of 3D volumetric models. Flaws inherent in current geospatial data models have greatly restricted the further development and application of the first-generation Digital Earth systems. For geoscientists and software developers of Digital Earth systems, an important goal is to design and develop a new Digital Earth system that supports both 3D vector and 3D volumetric data models.

As with other existing Digital Earth systems, we use an integrated data model to describe and represent multi-source geospatial information with full dimensionality. But unlike previous Digital Earth systems, this integrated data model not only involves the integration of 2D/2.5D data models and 3D vector data models, but also extends to the integration of 3D volumetric data models.

Figure 1 gives an overview of how different geospatial data are represented and integrated in SolidEarth. The geospatial data are classified into ten different types: 1) remote-sensing image, 2) digital elevation model, 3) map, 4) geologic map, 5) 3D structure model for atmosphere, 6) 3D property model for atmospheric space environment elements, 7) 3D geological structure model, 8) 3D geological property model, 9) 3D ground object model, and 10) observed & probing data.

The 2D raster data model is suitable to express remote-sensing image data. Map and geologic map data can be expressed by 2D vector data model. To express digital elevation models, the 2.5D DEM data model is the most appropriate choice. To express 3D structure models for

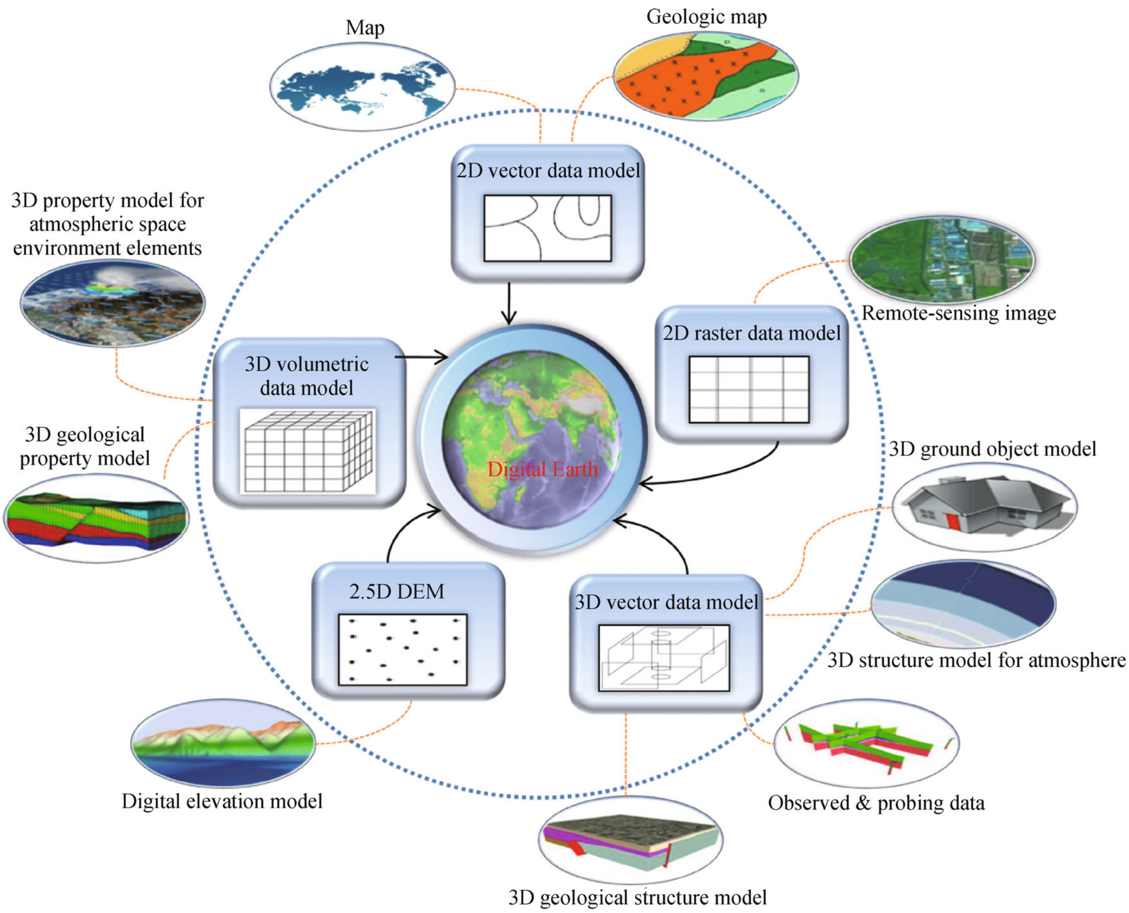

Fig. 1 Classification of geospatial information and geospatial data model.

atmosphere, 3D geological structure models, 3D ground object models, and observed & probing data, we use a 3D vector data model which is based on boundary representation (BRep).

The 3D property model for atmospheric and geological space can be represented by a set of values on a latitude, longitude, and depth 3D grid covering the exterior and interior of the Earth (Postpischl et al., 2011). Atmospheric or geological property values are attached to corresponding mesh units (voxels) which spread over the whole Earth space. Therefore, to express the 3D property model within atmospheric and geological space, we use Geocellular voxels (Denver and Phillips, 1990; Wu, 2004; Turner, 2006) as the base of 3D volume solids. As a mutant of the 3D-raster structure, Geocellular has a normal latitude-longitude grid partition in the lateral direction (Fig. 2(a)), while the spatial partition along the vertical direction is not invariable, but changed according to the actual data fields or the controlling interface of geospatial objects (Fig. 2(b)). Geocellular supports predictive modeling in 3D with its remarkable characteristic of simplicity, commonality, stability, suitability for multi-scale subdivision and self-adaptive visualization of the Earth space, high-efficiency, and practicability. Using this partly deformable Geocellular structure, we can successfully create arbitrary fine 3D grids to simulate actual spatial distributions of property fields by adaptively subdividing the Earth space.

It should be pointed out that all geospatial models, whether 2D or 2.5D, must be converted and integrated into a universal 3D space defined by the Digital Earth virtual globe environment. Using 2.5D digital elevation models, we can directly construct terrain models in 3D since DEMs have elevation information for the third spatial dimension. 2D data, such as remote-sensing images, maps, and geologic maps, can be considered as ground overlays which can be draped over the terrain model of the Earth, or hanged over the Earth’s surface at proper altitudes (de Paor and Whitmeyer, 2011).

4 Modeling the Earth in 3D

As noted above, there are six types of 3D geospatial data that need to be displayed and analyzed in Digital Earth platforms (shown in Section 3.2): observed & probing data, 3D ground object model, 3D structure model for atmosphere, 3D geological structure model, 3D property model for atmospheric space environment elements, and

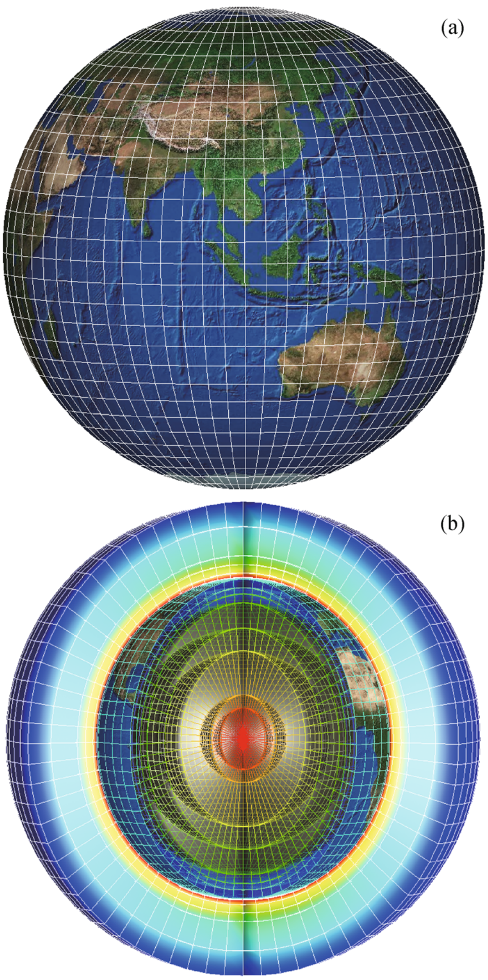

Fig. 2 Geocellular voxel structure applied to 3D property models. (a) Geocellular employs a normal latitude-longitude grid as the basis for the spatial partition in the lateral direction. (b) The spatial partition along the vertical direction is deformable according to the actual data fields or the controlling interface of geospatial objects.

3D geological property model. Among them, the first two types are modeling results which are constructed from partial, scattered sample data obtained from field measurements; the other four types are relevant to the construction of the Earth model. Then, we can lump them together under the research field of modeling the Earth in 3D.

Representing observed & probing data or building 3D ground object models are relatively simple tasks. Using several often-used 3D modeling software tools like Sketchup, AutoCAD, 3D Studio Max, and Maya, models can be defined independently of Digital Earth platforms in their own coordinate space, and constructed and saved as a general interchange file format (such as COLLADA file types). After attaching geographic coordinate information, models can be imported into Digital Earth systems, and can be translated, rotated, and scaled to fit into the Earth coordinate system (de Paor and Whitmeyer, 2011).

In Digital Earth systems, how to reconstruct 3D Earth models at different levels, including local, regional, and global scales, is a critical problem faced by geoscientists of all disciplines. The Earth has a complex geometric structure and its properties are changeable across geospatial locations. Earth models are mathematical models that can be used to describe the geometric structures and spatial distributions of property element fields within both inner and outer spheres of the Earth. In principle Earth models have to be 3D and able to represent structures and properties in the whole Earth space. Therefore, we can broadly separate the Earth models into two categories: structure models that give the boundaries between different defined geospatial units (Turner, 2006; Zhu et al., 2012); and property models that reflect the spatial distributions of geospatial property element fields, including atmospheric space environment elements (such as atmospheric density, temperature, stress, composition, etc) and geological properties (such as seismic velocity, elastic modulus, gravity, etc.) (Wang et al., 2005; Royse et al., 2009) . Those two types of models should be constructed in two different ways.

Based on the most popular existing global structural models, control interfaces for each sublayer of earth spheres are drafted under the constraints of actual observed and probing data sets. Then a BRep-based 3D structure model for the Earth is generated using properly constructed methods (Wu, 2004; Turner, 2006; Zhu et al., 2012). The most popular existing global structural models include the IASP91 Earth model (Kennett et al., 1995), the Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson, 1981), the global crustal model CRUST 5.1 (Mooney et al., 1998) and its updated version CRUST 2.0, and the atmospheric structural model.

Property models can be constructed using mathematical simulations. In recent years, geoscientists have developed a series of sophisticated numerical models to quantitatively simulate the average distributions of geospatial property elements from a macroscopic view (Wang et al., 2005). The Preliminary Reference Earth Model (PREM) describes the variation of elastic properties and density in the interior of the Earth (Dziewonski and Anderson, 1981). The International Reference Ionosphere model (IRI-2001) provides densities, composition, and temperatures of the ionosphere (Bilitza, 2001).The MSIS-2000 neutral atmosphere model describes the major variations of the temperature and densities in the neutral atmosphere (Picone et al., 2002). Based on those numerical models, we can create acceptable 3D property models for various property element fields. As shown in Fig. 3, the generation of a 3D property model is based on the following steps:

Step 1: Using existing numerical models for geospatial property elements, generate the Geocellular-based data fields for various property elements (denoted as F_1);

Step 2: Discretize observed and probing sample data for property elements to generate scatter-point-based sample data fields (denoted as F_2);

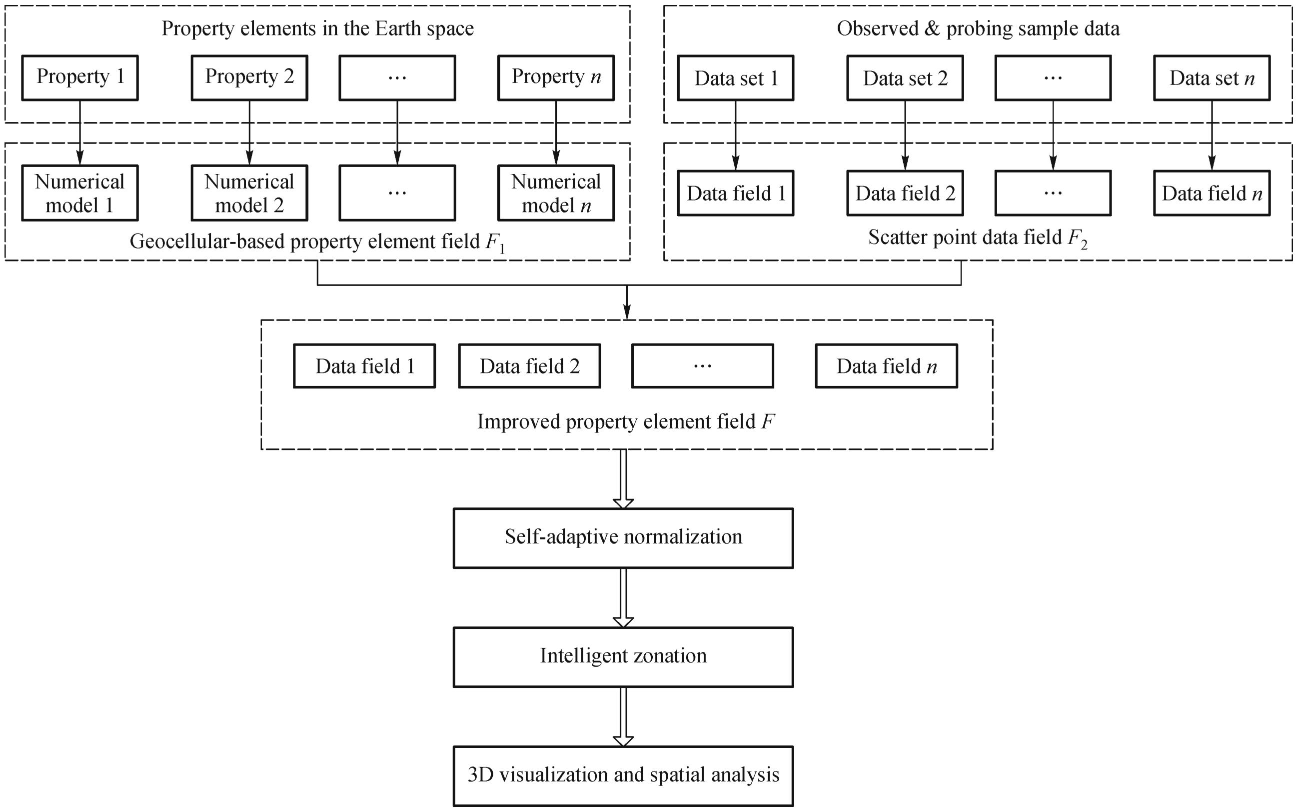

Fig. 3 Modeling flow of geospatial property elements in 3D.

Step 3: Optimize and adjust F_1 with the restriction of the sample data extracted from F_2, and generate the improved property element data fields (denoted as F);

Step 4: Self-adaptively normalize data sets in F to bring them into a range that is more familiar or normal to human vision;

Step 5: Intelligently zone normalized F into a series of proximate data sets using clustering procedure, convert the Geocellular-based data structure into 3D isosurface prior to display;

Step 6: Render, display and analyze the modeling result in 3D.

5 Multi-scale representation and self-adaptive visualization of 3D geospatial information

During the modeling and visualization process for 3D geospatial objects, challenges arise in the rapid access, timely updating, and real-time rendering of geospatial models when the geometric shapes of the models are complicated and the volume of data is huge. In order to enhance the efficiency of visualizing large volumes of 3D geospatial information on the Internet, we propose a systematic framework, within which the multi-scale representation of 3D geospatial information is implemented to transmit and visualize 3D geospatial models in SolidEarth. This framework includes a multi-scale models organization method with a level of detail (LOD) rendering strategy, and a web-based data transmission and self-adaptive visualization workflow suited for all types of geospatial models.

5.1 Multi-scale representation of 3D geospatial objects

In geosciences, scale means the LOD describing certain spatial objects within certain earth space. In the Digital Earth system, the viewer may perform a trans-scale roaming operation in the virtual scene since the scale of 3D scene is automatically changing with viewpoint. As a rule, the closer the distance from the viewer to the visualized object becomes the more small details of the object become distinguishable; the greater the distance becomes the more small details become indistinguishable (Bernardin et al., 2011). Thus, multi-scale representation of 3D geospatial objects, mainly embodied with different LODs, is necessary when rapid, continuous visualization and analysis is needed.

LOD, which provides real-time, high-quality rendering for 3D computer graphics, usually refers to generating and delineating a series of target models, in which details are changing gradually, from a source model. Based on the natural principle for objective generation (Li and Openshaw, 1993), those who are smaller, farther from the viewer, or less important in a 3D scene are drawn with less detail in order to achieve a tradeoff between system performance and visualization fidelity.

LOD can be classified into two different types: static LOD, and dynamic LOD, depending on their generating methods and application fields. In SolidEarth, we need to apply different LOD strategies to deal with different types of 3D geospatial objects since these models have different representations and characteristics.

The dynamic LOD strategy is suited for 3D volumetric models, appropriate for simplification and subdivision. Starting at the finest resolved 3D volumetric model in which full details are provided, we can generate a series of coarse resolved models with different scales by using real-time reduction algorithms for dynamic LOD. When models are transmitted on the Internet and visualized by the client, we can choose the proper model with a reasonable LOD according to the distance from the center of the model to the viewpoint, avoiding invariably using the finest resolved model. The dynamic LOD strategy not only can greatly reduce the data flow transmitted on the Internet and the voxel quantity in 3D scenes, but also can ensure the consistency of the geometry data and the continuity of the vision through stable, smoothing transitions between adjoining LODs.

By contrast, the static LOD strategy is propitious to apply to 3D vector models. The jumping between adjoining LODs is tolerable, because those models are zooming in or zooming out in 3D scenes. We generate more than one copy of a 3D vector model. Each copy corresponds to a particular resolution, and all copies are consolidated and saved into the database to construct the corresponding pyramid structure. When models need to be transmitted and displayed, the proper model with a reasonable LOD is chosen automatically based on current viewing parameters, such as the distance from the model to the viewpoint, the pixel area of the model projected into image space, or the intensity of illumination.

5.2 Network transmission and self-adaptive visualization of 3D geospatial information

Limited by current network bandwidth and transferring speed, existing Digital Earth systems, such as Google Earth, adopt spatially tiled structure, multi-scale representation, and progressive transmission methods in order to publish massive, high-resolution remote-sensing images and other available geographic data on the Internet (Butler, 2006; Craglia et al., 2008). These approaches drastically enhance the capabilities of the Internet by reducing the size of file transfers, and allowing near-real-time visualization and analysis of multiple large data sets on a decent broadband connection. Taking advantage of these approaches in a fashion similar to the existing first-generation Digital Earth systems (Zhang et al., 2009) we propose a web-based data transmission and self-adaptive visualization workflow suited for all types of geospatial information, especially 3D geospatial models.

As shown in Fig. 4, all 3D geospatial data are integrated and stored in the geospatial database on the server side. Since vector and volumetric models have different representations, we need to apply different methods to deal with these models. For a given vector geospatial object, we store a series of 3D vector models with multiple scales or resolutions in the geospatial database. However, for a given voxel geospatial object, we only store one 3D volumetric model, termed M_{vol}, with a single scale and highest resolution in the geospatial database. Thus, the server side needs to adopt the pre-determined model reduction algorithms (such as progressive meshes method) to simplify M_{vol} in order to quasi-instantly generate multi-scale volumetric models with lower resolution according to the requests of the client.

In this workflow, once the server side receives the data requests sent by the client side, the server immediately retrieves the geospatial database through the 3D spatial index, such as LOD-R tree (Zhu et al., 2007), to acquire the proper models with certain ranges and details most appropriate for current viewing parameters. And subsequently, the acquired models are progressively transmitted to the client. And finally, the client creates cache files for the acquired models. Display and analysis can be successfully accomplished in the visualization component of the client.

In the process of client visualization, we use the focus-context approach to display massive geospatial information in a full, constant, and coherent operation. The focus-context approach allows users to view not only those areas of interest to viewers with the most accurate geometric representation, but also the overall impression of the surrounding regions relevant to the focus in a lower resolution (Bernardin et al., 2011). The combination of the above approaches leads to the viewpoint-based transformation and self-adaptive visualization of 3D geospatial data, and improves responsiveness and interactivity for visualization and analysis on the client side.

6 System implementation

To demonstrate the effectiveness of our proposed approaches, SolidEarth (Fig. 5), an experimental system that is designed for the purpose of modeling and analyzing the whole Earth space, was programmed in Microsoft Visual C++, AVS/Express [1)], and the OpenGL graphics

1) Advanced Visual Systems Inc (2012). AVS/Express overview. Available from: http://help.avs.com/Express/doc/help_80/books/usersguide/UG01overview.html#893339 [Accessed 23 January 2013].

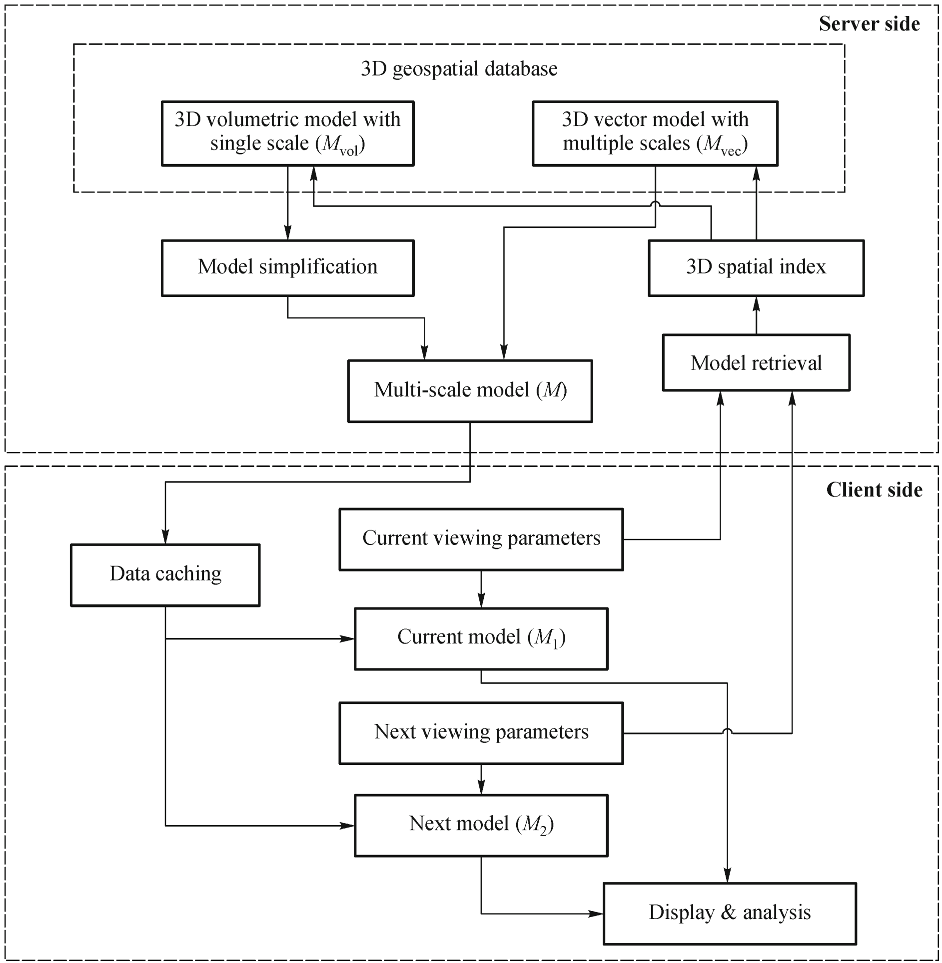

Fig. 4 Network transmission and self-adaptive visualization of 3D geospatial information.

library, on the PC platform. As a prototype application of the next-generation Digital Earth system, SolidEarth inherits plenty of basic functions that have been implemented in the first-generation Digital Earth system, focusing on comprehensively validating the modeling, visualization, integration, and analysis of geospatial objects existing in the entire Earth space. SolidEarth consists of four basic functional components that are discussed in the following sections: modeling in geographical space, modeling in geological space, modeling in atmospheric space, and integrated visualization and analysis.

6.1 Modeling in geographical space

As with existing Digital Earth systems, the fundamental geographical data from a variety of resources, including remote-sensing images, topography data, digital maps, ground object models, and other available geographical contexts, can be meshed, integrated, and published within SolidEarth. Based on these data, both displaying global geographical objects and subsequent analysis can be accomplished from macro-vision to micro-detail in a 3D virtual global environment. Users can build digital elevation models using high-resolution terrain data to measure global topography and how it varies in 3D space. As Fig. 6 shows, satellite and aerial images can be fused into terrain models to restore the 3D shape of the Earth's surface. Thematic maps, such as user-defined regions of interest (ROI), social, economic, infrastructure, and environmental data, can be imported into SolidEarth and draped over the underlying terrain models.

6.2 Modeling in geological space

The most distinctive function of SolidEarth is that of building 3D solid models in geological space to image the structural characteristics of geological objects, the spatial distributions of geological properties, and the spatial correlations between different geological units, at both local and planetary scales. Solid models of geological objects in 3D can provide detailed definition of the boundaries and properties of different phenomena and complex structures, and then help to predict the spatial

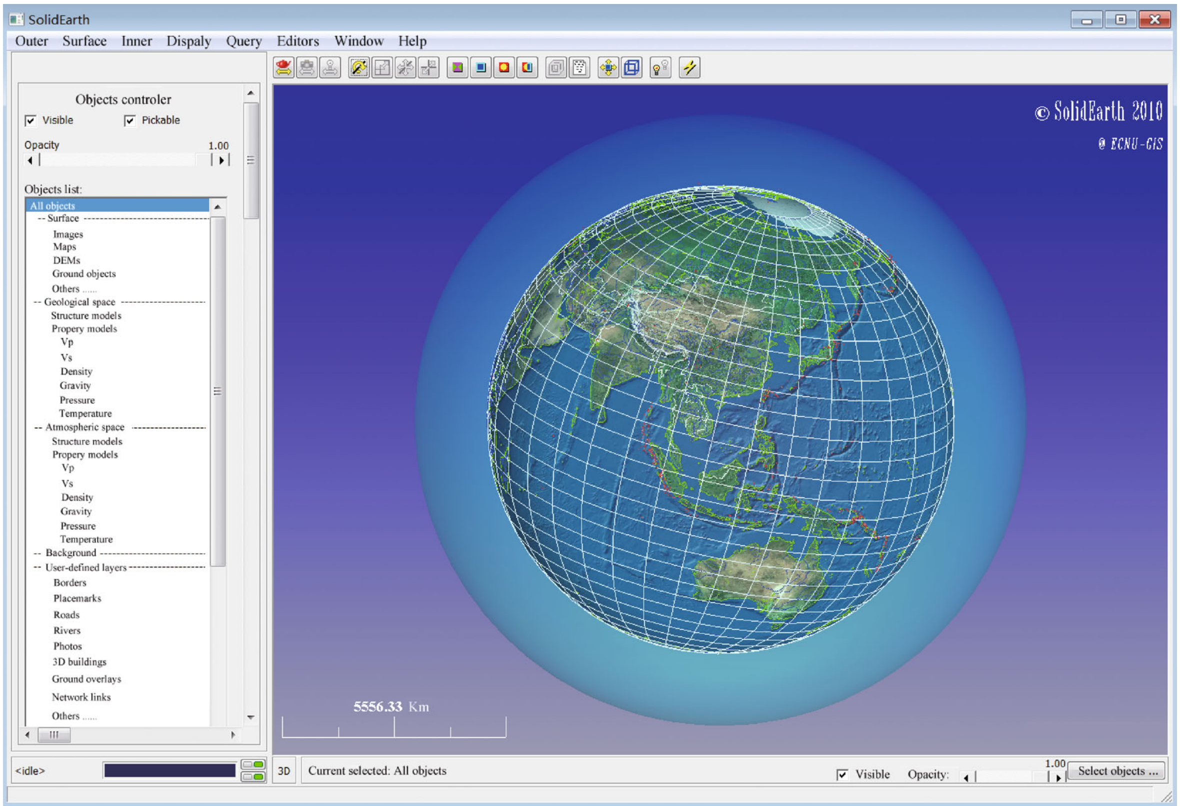

Fig. 5 User interface of client side in SolidEarth.

variation of geological characterization within the Earth (Hack et al., 2006; Turner, 2006; Zhu et al., 2012). In SolidEarth, geological models are broadly separated into two categories (Hack et al., 2006; Turner, 2006): one is the structure model, which defines the geometric boundaries between different geological objects; another is the property element model, which defines the spatial distributions of physical, chemical, or other properties within different geological units.

SolidEarth adopts a boundary-representation-based (BRep-based) 3D vector data model for defining 3D structure models of various geological objects, including strata, faults, folds, intrusions, underground rivers, karst caves, ore bodies, oil/gas reservoirs, and other complex structures. In order to build geologically reasonable structure models, several often-used interpolation schemes, like the inverse distance weighted (IDW), natural neighbor, the nearest neighbor distance, radial basis function (RBF), and Kriging methods, are integrated into SolidEarth to interpolate the shapes of geological objects between widely spaced sample points. Furthermore, several more complex approaches to construct structurally complex or poorly sampled geo-objects, such as surface modeling, section modeling, and interactive modeling (Wu, 2004; Wu and Xu, 2004; Wu et al., 2005; Hack et al., 2006; Turner, 2006; Calcagno et al., 2008; Guillen et al., 2008), also can be applied in SolidEarth to overcome the disadvantages of 3D spatial interpolation. In addition, large quantities of probing data in a variety of formats, such as borehole, cross-section, and exploration seismic data, can be integrated into SolidEarth to successfully replicate actual spatial shapes and correlation relationships among different geological objects (Fig. 7).

SolidEarth offers an automatic process to construct 3D property models in geological space. This process involves two steps. In the first step, the geological space can be subdivided into a series of 3D volumetric meshes by applying discretization methods. Taking the fundamental geological framework defined by 3D geological structure models as spatial datum, SolidEarth automatically generates 3D volume solids that consist of large numbers of Geocellular voxels, and are constrained by the geometric framework of geological objects. In the second step, using representative sample data and the existing numerical pattern for a given geological property element, users adopt the construction methods for 3D geospatial property elements (shown in Section 4) to calculate geological property values attached to each Geocellular voxel. Thus, the final solid model filled with Geocellular voxels is built and then fed to the real-time visualization component of SolidEarth for subsequent visualization and 3D spatial analysis (Fig. 8).

With the advanced visualization tools provided by SolidEarth, users can freely explore 3D geological models

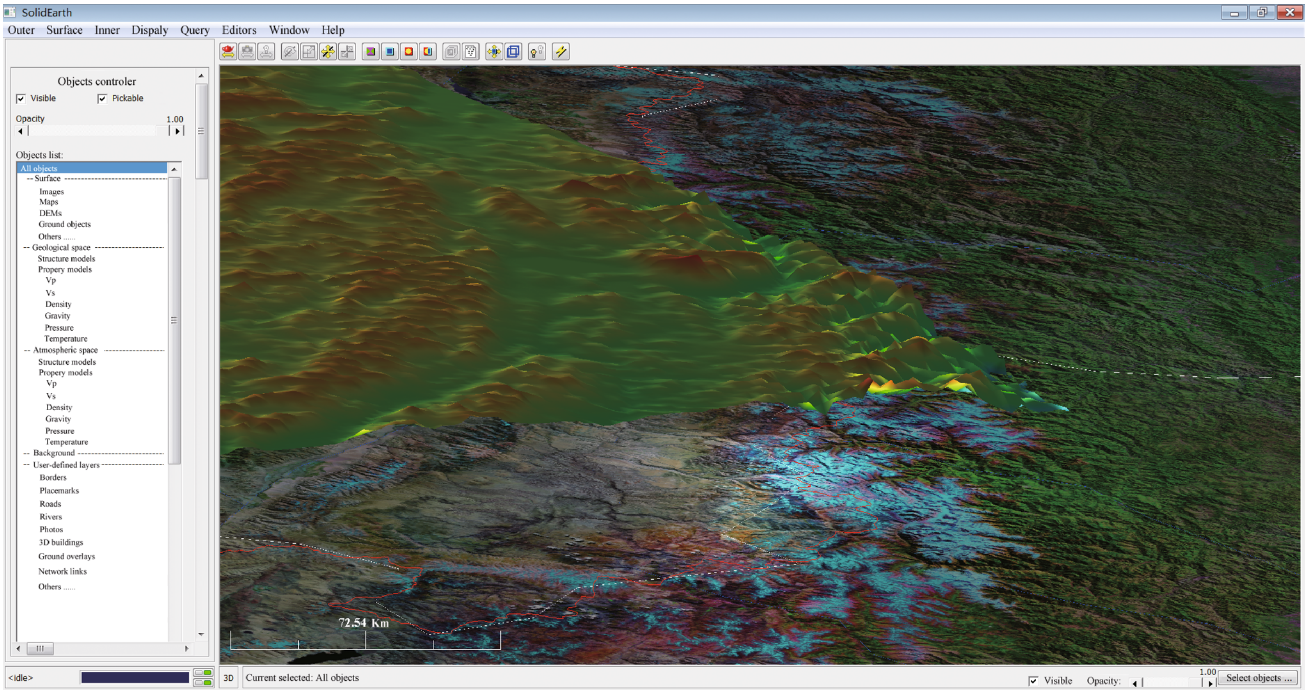

Fig. 6 Integration and visualization of geographic information relevant to the Earth's surface and near-surface in SolidEarth. This figure illustrates the integration and display of remote-sensing images, DEMs, and maps at the same view. Note that at the upper-left part of the screen only the terrain model is visible, whilst at other parts remote-sensing images and maps are draped over the underlying rugged terrain.

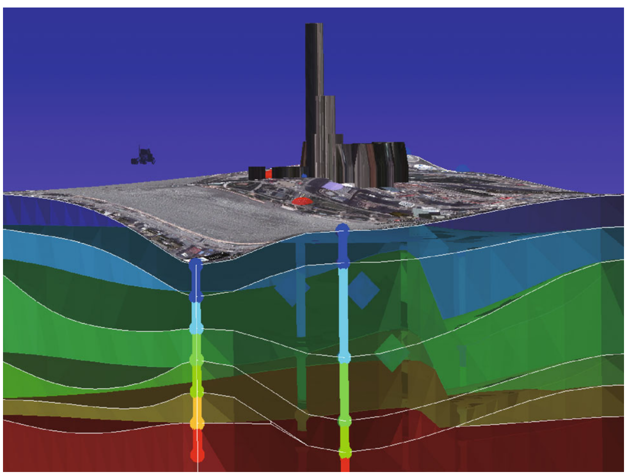

Fig. 7 Integration and visualization of geological structure model and geographic objects. This figure illustrates the integration, display, and analysis of remote-sensing images, DEMs, ground objects, and 3D solid models of geological structures generated from boreholes, at one view.

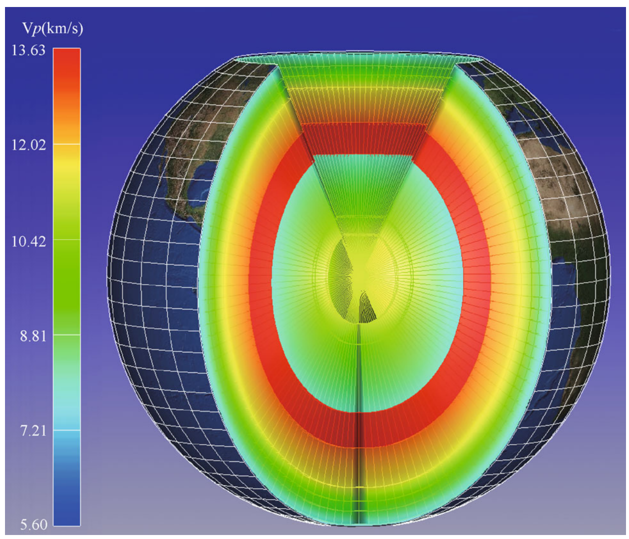

Fig. 8 Example of modeling and visualization for 3D geospatial property elements in SolidEarth. This figure illustrates an overview of the 3D spatial distribution of the compressional wave velocity (*Vp*) field within the interior space of the Earth.

with a vivid appearance in a variety of ways. Instead of hanging over or projecting onto the globe's surface (de Paor and Whitmeyer, 2011; Navin and de Hoog, 2011; Zhu et al., 2014), subsurface models are placed in the correct locations beneath the Earth's surface. Users can fly through the surface of the Earth, and roam virtually in geological space. Several operations for 3D-interaction of the solid model, such as 3D observation, slice up, arbitrary incision, virtual drilling, virtual roaming, spotting, and measurement of property value in any spatial position, excavation of foundation pit or tunnel, distance/area/volume calculation of particular geological unit, etc., can be performed freely, since the solid representation of geological space is very suitable for spatial analysis and spatial query (Fig. 9). All of the above functions open the eyes of users to the depth of the Earth, and will help to comprehensively recognize and research the composition, structure, property, and evolution of geological space that occurs beneath the surface of the Earth in an all-round, multi-view manner.

6.3 Modeling in atmospheric space

Similar to geospatial objects in geological space, there are two types of models that need to be constructed in atmospheric space: the structure model, which defines the stratified boundaries between different atmospheric layers; and the property model, which reflects the spatial distributions of atmospheric space environment element fields (Wang et al., 2005).

As opposed to geological spaces, which often have complicated, volatile, and discontinuous interfaces between different geological units, the geometric shape of atmosphere is relatively simple, as there are continuous interfaces between different sublayers. Thus, all sublayers in atmospheric space can be regarded as continuous stratified objects. Based on the existing stratification models and continuous updated probing data of atmosphere, SolidEarth adopts conventional solid modeling methods (Turner, 2006; Zhu et al., 2012) for geo-objects in order to construct structure models within atmospheric space.

SolidEarth provides users with a series of numerical patterns (such as IRI-2001, MSIS-2000, MET and HWM93) (Wang et al., 2005), global and regional climate/weather models, data processing schemes, and spatial interpolation methods to build 3D property models in atmospheric space. Depending on different distribution characteristics and application requirements, different 3D volumetric models, which correspond to different property element fields like density, temperature, stress, or composition of atmosphere, can be automatically generated and fed to the visualization component of SolidEarth to reveal the spatial variations of atmospheric space environment element fields (Fig. 10).

6.4 Integrated visualization and analysis

All geospatial models with a unified geographic coordinate system can be seamlessly integrated into a real-time, user-friendly visualization component of SolidEarth in order to carry out the visualization and geospatial analysis process. A general-purpose but powerful user interface for interacting with geospatial data is provided to manage, display, and analyze heterogeneous datasets from a wide range of sources and disciplines at one virtual scene.

In SolidEarth, we can integrate and visualize multiple types of geospatial objects/features simultaneously, from the structures and properties at a local level up to the changes and mechanisms between different geospatial objects at a global scale, in the correct location of the Earth space. The model can be updated quickly and easily when new probing data or numerical patterns become available. Through the use of advanced visualization techniques like layering stack, transparency setting, and focus-context visualization, geospatial objects in geographical, geological, and atmospheric space can all be viewed and compared at the same time (Fig. 11). Thus, SolidEarth provides the

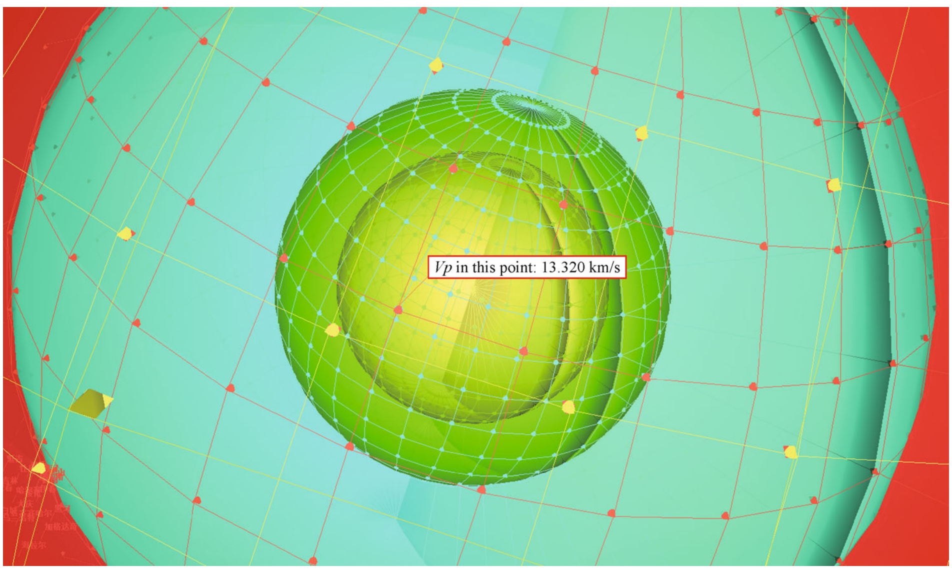

Fig. 9 Virtual roaming and spatial query of the property information within the interior space of the Earth. In SolidEarth, users can perform such operations as virtual roaming by swooping over geological space, spotting, and measurement of property value in any spatial position by clicking 3D solid models.

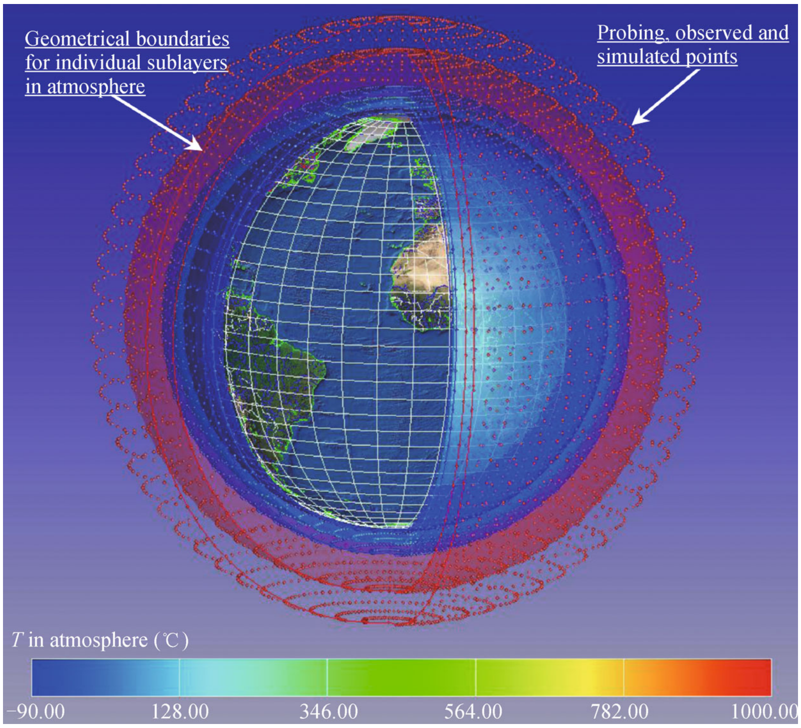

Fig. 10 Example of modeling and visualization in atmospheric space. In this figure, the geometrical boundaries for individual sublayers and the temperature field model in the atmosphere are integrated and visualized simultaneously. Note that the opacity for each sublayer in the atmosphere is increased from the interstellar space to the Earth's space.

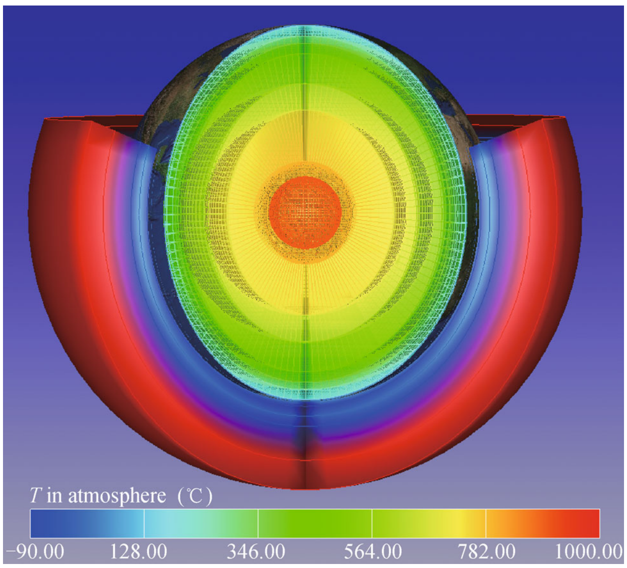

Fig. 11 Integration, visualization, and analysis of geospatial objects in geographical, geological, and atmospheric space. In this figure, the stratified boundaries between different atmospheric sublayers, the temperature field model within atmospheric space, remote-sensing images of the Earth's surface, and a 3D structural model of the interior Earth are integrated, displayed, and analyzed at the same view.

opportunity for geoscientists to detect and visually analyze spatial relationships and correlations between geographical, geological, and atmospheric objects. This could dramatically improve the efficiency of exploring relationships hidden behind the complex and large volume of geospatial data, lead to an increased comprehensive understanding of the whole Earth, and maybe produce new knowledge and promote new scientific discoveries.

7 Characteristics of SolidEarth

Compared with the first-generation Digital Earth system, the significant features and substantial advantages of SolidEarth are obvious:

1) Coherent representation, integrated access, and efficient management of multi-dimensional geospatial information. In SolidEarth, both two- and three- dimensional geospatial data sets from a wide range of sources and disciplines are expressed coherently in the Earth space; users can effectively access these massive, heterogeneous, and multi-resolution data sets that are obtained from multiple sources and many different disciplines.

2) Rapid modeling, seamless integration, and visual analysis for earth spheres. SolidEarth allows users not only to model geographical objects existing in the Earth's surface and near-surface areas, but also to effectively create 3D structure and property models of earth spheres. Moreover, all of those models can be integrated into a real-time, user-friendly visualization component of Soli-

dEarth in order to carry out the visualization and geospatial analysis process. With the advantages of 3D volume visualization, self-adaptive visualization, transparent display, texture mapping, and other new techniques that are synthetically applied to SolidEarth, it is convenient to implement interactive operations and near real-time visualization for large-scaled geospatial models in 3D, and to gain insight into the Earth's interior and exterior.

8 Application domains and user communities

SolidEarth is based on relatively recent advancements in remote sensing, geographic information science, and geospatial technologies, as well as developments in the modeling and visualization of multi-dimensional geospatial information. It offers users the capability to model, manage, display, and analyze 3D geospatial data characterized as large-extent, multi-scaled, multi-source, massive, and heterogeneous. The main potential user communities for SolidEarth are geoscientists and educators. As a powerful platform to make geospatial data more useful and user friendly, SolidEarth can support nearly all scientific domains and research projects that are broadly centered on gathering, modeling, analyzing, and interpreting geospatial information with full dimensionality in an integrated view. SolidEarth is expected to make a significant contribution to the description, understanding, prediction, and demonstration of 3D structures and property of the Earth on both local and planetary scales in a virtual global environment. Based on SolidEarth, it is convenient 1) to create refined, high-resolution, three- or four- dimensional structure and property models of earth spheres using large quantities of global observation data; 2) to develop professional analytical models for a number of ongoing and new geosciences research projects, such as global change simulation, geodynamics simulation, Earth system simulation, and construction of Digital Earth applications; 3) to intuitively reveal how changes in geological and atmospheric space affect the Earth's surface; 4) and to visually integrate refined models of earth spheres, geographic information, remote sensing images, deep exploration data, and traditional 2D GIS functions, with great flexibility to construct server and application systems of multi-dimensional, dynamic geospatial information.

9 Conclusions and future work

We have introduced SolidEarth as an alternative Digital Earth system for the modeling and visualization of geospatial information. SolidEarth marks a significant advancement in the field of Digital Earth science and technology, as it tries to combine advantages of the first-generation Digital Earth system with 3D modeling and analysis functions of earth spheres. It overcomes the limitations of the conventional 2D space partition scheme that distorts spatial relationships between geological, atmospheric, and geographical objects. The most significant feature of SolidEarth is that it has a comprehensive treatment of the third spatial dimension and a series of sophisticated, advanced 3D spatial analysis functions. Thus, it is well-suited to volumetric representations of the entire Earth space and the visual analysis of inner and outer spheres of the Earth, and eventually changes the way we interact with geospatial information.

Although our attempts have been to make SolidEarth as easy as possible for end users, the concrete functions and operations of SolidEarth, specifically designed for dealing with the full dimensionality of geospatial information, is still undergoing modification. Based on our work with the SinoProbe program (Dong et al., 2011) and our current research needs, we believe at least five priority aspects need further research and development:

1) Modeling and analysis of 3D vector fields in the Earth space. Vector fields, which have directions as well as sizes, such as gravity, electromagnetic, and flow field, are widely distributed in the Earth space. Visualization of 3D vector fields not only can display the directional information of those fields, but also may lead to new insights of spatial structure. We are planning to employ such techniques as data probe, advection, vector plot, and texture-based methods to perform 3D reconstruction and visual analysis of vector fields on SolidEarth.

2) XML-based access, management, and exchange of 3D volumetric models. Currently, XML-based markup languages like KML and CityGML have became the standard descriptive languages that are widely embraced by geoscientists as a means to represent geographical objects. However, those languages were not designed for the purpose of representing 3D volumetric models. Thus, they are not suited for the representation and exchange of atmospheric/geological objects over the Internet. In order to create, display, exchange, and share geospatial objects with full dimensionality, we should develop the XML-based distribution and exchange techniques for 3D Earth models, and the standardization and interoperation methods for 3D volumetric models in a web browser environment.

3) 3D visual analytic tools for geological applications. SolidEarth should be regarded as not only a visualization system for geospatial information, but also a geologic instrument that encourages virtual geologic investigation (Bernardin et al., 2011). In the future, more easy-to-use 3D analytic tools relevant to the needs of professional users, such as the virtual geologic compass, and 3D model editor, need to be integrated into SolidEarth as auxiliary support for geological and geophysical analysis.

4) Assessment and representation of uncertainty in 3D geospatial data and models. Up to now it has been difficult to make effective assessments of the precision of geospatial models according to a unified and flexible mode. In the future, a series of sophisticated models relevant to the assessment and representation of uncertainty in 3D geospatial data/models, such as the general theoretical model of accuracy assessment for geospatial data/models, the practical operating model for given geospatial objects, and the 3D spatial distribution model for uncertainty in geospatial data/models (Zhu and Zhuang, 2010), need to be developed and integrated into SolidEarth to meet the special concern on the issues of uncertainty in the scientific community (Goodchild et al., 2012).

5) Dynamic visualization and analysis techniques for temporal geospatial information. Because the Earth is three-dimensional in space and can be viewed as four-dimensional when time is considered (Hack et al., 2006; Li et al., 2011), future improvements to SolidEarth include the need to robustly handle spatio-temporal data that reflect the dynamic process of earth spheres. We should combine the temporal GIS technique with SolidEarth to simulate structures and properties of the entire Earth using geospatial data in four dimensions (latitude, longitude, altitude, and time).

Acknowledgements This research was supported by the National Science and Technology Program of China (Grant No. SinoProbe-08), the National Natural Science Foundation of China (Grant No. 40902093), the National Social Science Foundation of China (Grant No. 07CZZ019), the Development Foundation of Experimental Teaching Equipment in East China Normal University (Grant No. 64100010) and the Open Foundation of Shanghai Key Lab for Urban Ecological Processes and Eco-Restoration (Grant No. SHUES2011A06). We would like to thank the Editor and two anonymous reviewers for their helpful and constructive suggestions for improving the paper.

References

Bailey J E, Chen A (2011). The role of Virtual Globes in geoscience. Comput Geosci, 37(1): 1–2

Bernardin T, Cowgill E, Kreylos O, Bowles C, Gold P, Hamann B, Kellogg L (2011). Crusta: a new virtual globe for real-time visualization of sub-meter digital topography at planetary scales. Comput Geosci, 37(1): 75–85

Bilitza D (2001). International Reference Ionosphere 2000. Radio Sci, 36(2): 261–275

Butler D (2006). Virtual globes: the web-wide world. Nature, 439(7078): 776–778

Calcagno P, Chilès J P, Courrioux G, Guillen A (2008). Geological modelling from field data and geological knowledge: part I. Modelling method coupling 3D potential-field interpolation and geological rules. Phys Earth Planet Inter, 171(1–4): 147–157

Craglia M, de Bie K, Jackson D, Pesaresi M, Remetey-Fülöpp G, Wang C, Annoni A, Bian L, Campbell F, Ehlers M, van Genderen J, Goodchild M, Guo H, Lewis A, Simpson R, Skidmore A, Woodgate P (2012). Digital Earth 2020: towards the vision for the next decade. Int J Digital Earth, 5(1): 4–21

Craglia M, Goodchild M F, Annoni A, Camara G, Gould M, Kuhn W, Mark D, Masser I, Maguire D, Liang S, Parsons E (2008). Next-generation Digital Earth: a position paper from the Vespucci Initiative for the advancement of Geographic Information Science. Int J Spatial Data Infrastructures Res, 3: 146–167

de Floriani L, Falcidieno B (1988). A hierarchical boundary model for solid object representation. ACM Trans Graph, 7(1): 42–60

De Paor D G, Whitmeyer S J (2011). Geological and geophysical modeling on virtual globes using KML, COLLADA, and Javascript. Comput Geosci, 37(1): 100–110

Denver L F, Phillips D C (1990). Stratigraphic geocellular modeling. Geobyte, 5: 45–47

Dong S, Li T, Gao R, Hou H, Li Q, Li Y, Zhang S, Keller G R, Liu M (2011). A multidisciplinary Earth science research program in China. Eos Trans AGU, 92(38): 313–314

Dziewonski A M, Anderson D L (1981). Preliminary reference Earth model. Phys Earth Planet Inter, 25(4): 297–356

Fowler C M R (2005). The Solid Earth: An Introduction to Global Geophysics (2nd ed). Cambridge: Cambridge University Press, 685

Goodchild M F (2008). The use cases of digital earth. Int J Digital Earth, 1(1): 31–42

Goodchild M F (2012). Discrete global grids: retrospect and prospect. Geography and Geo-Information Science, 28(1): 1–6

Goodchild M F, Guo H, Annoni A, Bian L, de Bie K, Campbell F, Craglia M, Ehlers M, van Genderen J, Jackson D, Lewis A J, Pesaresi M, Remetey-Fülöpp G, Simpson R, Skidmore A, Wang C, Woodgate P (2012). Next-generation Digital Earth. Proc Natl Acad Sci USA, 109(28): 11088–11094

Gore A (1999). The Digital Earth: Understanding our planet in the 21st Century. Photogramm Eng Remote Sensing, 65: 528–530

Guillen A, Calcagno P, Courrioux G, Joly A, Ledru P (2008). Geological modelling from field data and geological knowledge: part II. Modelling validation using gravity and magnetic data inversion. Phys Earth Planet Inter, 171(1–4): 158–169

Guo H (2012). Digital Earth: a new challenge and new vision. Int J Digital Earth, 5(1): 1–3

Hack R, Orlic B, Ozmutlu S, Zhu S, Rengers N (2006). Three and more dimensional modeling in geo-engineering. Bull Eng Geol Environ, 65(2): 143–153

Jones C B (1989). Data structures for three-dimensional spatial information systems in geology. Int J Geogr Inform Syst, 3: 15–31

Kennett B L N, Engdahl E R, Buland R (1995). Constraints on seismic velocities in the Earth from traveltimes. Geophys J Int, 122(1): 108–124

Li J, Wu H, Yang C, Wong D W, Xie J (2011). Visualizing dynamic geosciences phenomena using an octree-based view-dependent LOD strategy within virtual globes. Comput Geosci, 37(9): 1295–1302

Li Z, Openshaw S (1993). A natural principle for the objective generalization of digital maps. Cartography and Geographic Information Systems, 20(1): 19–29

Martínez-Graña A M, Goy J L, Cimarra C A (2013). A virtual tour of geological heritage: valourising geodiversity using Google Earth and QR code. Comput Geosci, 61: 83–93

Mooney W D, Laske G, Masters T G (1998). CRUST 5.1: a global crustal model at 5°×5°. J Geophys Res, 103(B1): 727–747

Navin J, de Hoog M (2011). Presenting geoscience using virtual globes.

AusGeo News, 104: 15–19

Picone J M, Hedin A E, Drob D P, Aikin A C (2002). NRLMSISE-00 empirical model of the atmosphere: statistical comparisons and scientific issues. J Geophys Res, 107(A12): 1468–1483

Postpischl L, Danecek P, Morelli A, Pondrelli S (2011). Standardization of seismic tomographic models and earthquake focal mechanisms data sets based on web technologies, visualization with keyhole markup language. Comput Geosci, 37(1): 47–56

Royse K R, Rutter H K, Entwisle D C (2009). Property attribution of 3D geological models in the Thames Gateway, London: new ways of visualising geoscientific information. Bull Eng Geol Environ, 68(1): 1–16

Shen D, Wong D W, Camelli F, Liu Y (2013). An ArcScene plug-in for volumetric data conversion, modeling and spatial analysis. Comput Geosci, 61: 104–115

Turner A K (2006). Challenges and trends for geological modelling and visualization. Bull Eng Geol Environ, 65(2): 109–127

Wang P, Xu Q, Li J S (2005). 3D modeling and visualization simulation of near-earth space environment elements. Journal of System Simulation, 17: 2957–2960 (in Chinese)

Wang Y, Huynh G, Williamson C (2013). Integration of Google Maps/ Earth with microscale meteorology models and data visualization. Comput Geosci, 61: 23–31

Wu L X (2004). Topological relations embodied in a generalized tri-prism (GTP) model for a 3D geoscience modeling system. Comput Geosci, 30(4): 405–418

Wu Q, Xu H (2004). On three-dimensional geological modeling and visualization. Sci China Earth Sci, 47(8): 739–748

Wu Q, Xu H, Zou X (2005). An effective method for 3D geological modeling with multi-source data integration. Comput Geosci, 31(1): 35–43

Yang C, Raskin R, Goodchild M, Gahegan M (2010). Geospatial cyberinfrastructure: past, present and future. Comput Environ Urban Syst, 34(4): 264–277

Yu J Q, Wu L X, Zi G J, Guo Z Z (2012). SDOG-based multi-scale 3D modeling and visualization on global lithosphere. Sci China Earth Sci, 55(6): 1012–1020

Yu L, Gong P (2012). Google Earth as a virtual globe tool for Earth science applications at the global scale: progress and perspectives. Int J Remote Sens, 33(12): 3966–3986

Zhang L Q, Guo Z F, Kang Z Z, Zhang L X, Zhang X M, Yang L (2009). Web-based visualization of spatial objects in 3DGIS. Sci China Inform. Sci., 52: 1588–1597

Zhu L, Wang X, Zhang B (2014). Modeling and visualizing borehole information on virtual globes using KML. Comput Geosci, 62: 62–70

Zhu L, Zhang C, Li M, Pan X, Sun J (2012). Building 3D solid models of sedimentary stratigraphic systems from borehole data: an automatic method and case studies. Eng Geol, 127: 1–13

Zhu L, Zhuang Z (2010). Framework system and research flow of uncertainty in 3D geological structure models. Min Sci Technol, 20: 306–311

Zhu Q, Gong J, Zhang Y (2007). An efficient 3D R-tree spatial index method for virtual geographic environments. ISPRS J Photogramm Remote Sens, 62(3): 217–224