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Review of data storage and management technologies for massive remote sensing data

LÜ XueFeng[1], CHENG ChengQi[1*], GONG JianYa[2] & GUAN Li[3]

[1] Institute of Remote Sensing and GIS, Peking University, Beijing 100871, China;
[2] State Key Laboratory for Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan 430079, China;
[3] Beijing Institute of Surveying and Mapping, Beijing 100038, China

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Aiming at the storage and management problems of massive remote sensing data, this paper gives a comprehensive analysis of the characteristics and advantages of thirteen data storage centers or systems at home and abroad. They mainly include the NASA EOS, World Wind, Google Earth, Google Maps, Bing Maps, Microsoft TerraServer, ESA, Earth Simulator, GeoEye, Map World, China Centre for Resources Satellite Data and Application, National Satellite Meteorological Centre, and National Satellite Ocean Application Service. By summing up the practical data storage and management technologies in terms of remote sensing data storage organization and storage architecture, it will be helpful to seek more suitable techniques and methods for massive remote sensing data storage and management.

remote data storage, data management, storage architecture, data organization

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1 Introduction

With the development of satellite observing systems for the Earth, remote sensing data increases day by day, and forms an explosive growth trend from GB level to PB level. Meanwhile, the data takes on multi-source, multi-scale, multi-temporal, high-resolution and global coverage characteristics. How to more orderly and efficiently store and manage massive remote sensing data, form a unified storage organization standard (spatial reference, scale, temporal and semantic), and achieve rapid sharing and distribution of remote sensing information, has become one of the key issues of concern to spatial information science research, business application departments and agencies [1–7].

As the practical applications and services of remote sensing data always directly correlate with their geospatial locations, one important aspect of the efficient storage problem of massive remote sensing data lies in integrating the data's spatial characteristics to establish a rational, scientific and unified storage organization model and its corresponding storage structure for global remote sensing data. In this paper, thirteen data storage centers or systems, which mainly include the NASA EOS, World Wind, Google Earth, Google Maps, Bing Maps, Microsoft TerraServer, ESA, Earth Simulator, GeoEye, Map World, China Centre for Resources Satellite Data and Application (CCRSDA), National Satellite Meteorological Centre (NSMC) and National Satellite Ocean Application Service (NSOAS), are taken as the practical examples. First of all, the characteristics and advantages of these data storage and management technologies at home and abroad are described respectively from two main aspects: remote sensing data storage organization and storage architecture. Secondly, this paper makes a

*Corresponding author (email: ccq@pku.edu.cn)

comprehensive comparison and analysis so that it will be helpful to establish global remote sensing data storage model and make it more suitable for massive remote sensing data storage and management.

2 Foreign remote sensing data storage and management technologies

2.1 NASA EOS data centers

The NASA Earth Observing System (EOS) is mainly composed of Space Observing Platform, Earth Observing System Data and Information System (EOSDIS), and Scientific Research Program. Among them, the EOSDIS is a solution to the NASA EOS data storage and management [8].

2.1.1 EOS data volume and storage problems

The EOS data coves various Earth science fields, such as atmosphere, land, ocean, vegetation, snow and ice, and so on. Moreover, the data has global, multi-source and multi-scale characteristics. According to annual data statistics by NASA (http://esdis.eosdis.nasa.gov/eosdis/systemmetrics.html), the average daily archive growth exceeds 2 TB d^{-1}, the average daily distribution volume to end users overruns 9 TB d^{-1}, and the total archive volume is close to 5 PB.

Facing massive EOS data storage and management, EOSDIS has experienced three difficult stages [9, 10]. In 1995, the biggest problem was how to store and manage all EOS data, that is, how to store all the data firstly. After 10 years, in 2005, the biggest question was how to help users quickly find any data they need in the vast data and quickly distribute it to them. With the development of the scale of EOS data storage and management, the current problem is how to store and maintain EOS data in a more efficient and low-cost way.

2.1.2 Storage architecture and advantages of the EOSDIS

The EOSDIS adopts a distributed architecture and classifies each Distributed Active Archive Centre (DAAC) in accordance with Earth science disciplines. Each DAAC is responsible for managing a particular discipline of EOS data products and user services. As shown in Figure 1, the EOSDIS consists of two major parts: the mission system and the science system. The science system is responsible for archiving, managing and distributing data products; the mission system is responsible for commanding and controlling EOS satellites and sensors, data acquisition and initial (level 0) processing. Among them, most of EOS standard data products, which are defined from level 0 to level 4, are produced by the science investigator-led processing systems (SIPSs). At present, there are fourteen SIPSs geographically distributed across the United States. SIPSs are also responsible for delivering the resulting standard data products to the corresponding DAACs for archive and distribution [11].

At present, EOSDIS consists of twelve DAACs. In the plan, the EOSDIS Core System (ECS) is the common software and hardware system deployed at each DAAC and provides data ingestion, archive, distribution, and user services. For the physical storage architecture of the ECS, the

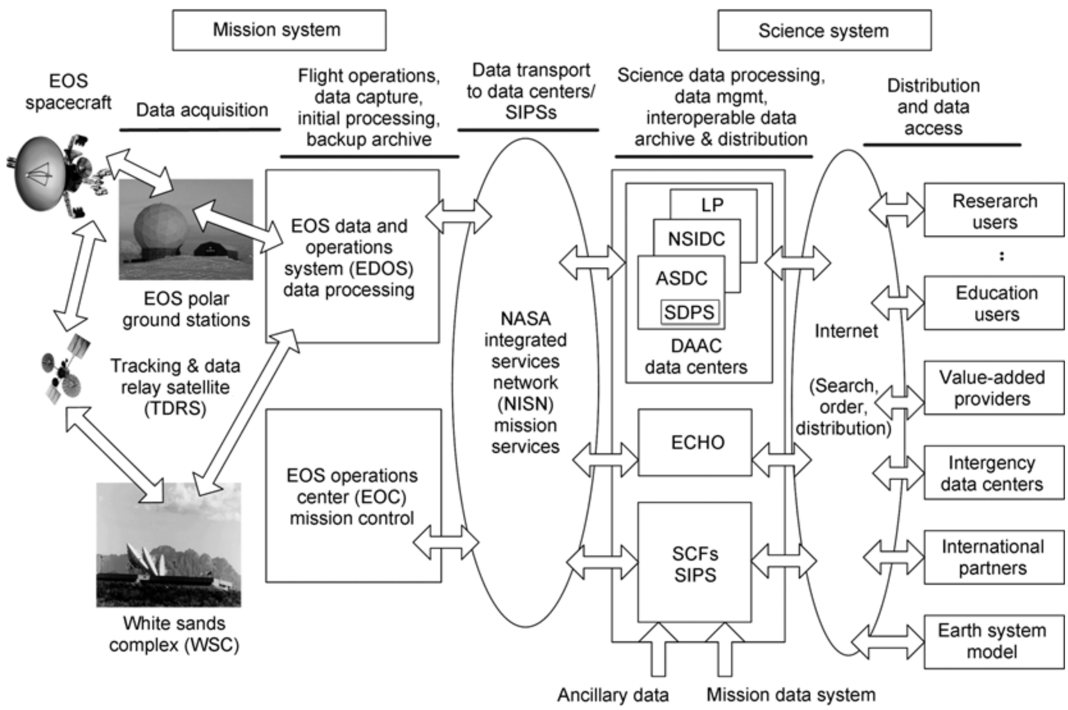

Figure 1 Overall system architecture of the EOSDIS.

majority of the data is stored and managed in the tape-based near-line way, and the data pool of the online data service system adopts the high-performance storage area network (SAN) and provides FTP or Web services. For data management software, the ECS adopts a combination of the commercial off-the-shelf (COTS) and custom software. In addition, a unified software toolkit is used for conveniently transferring data products among computing facilities (SCFs), SIPSs and DAACs [11]. The highlights of the data storage technologies and methods of the EOSDIS consist in the following three aspects.

One is that the entire system adopts a unified data storage format. In order to effectively store the geographic location data and provide a unified access interface for all types of EOS data products in the distributed environment, the EOSDIS adopts an extended hierarchical data format as EOS data standard format, namely HDF-EOS. Three geospatial data types of HDF-EOS (point, grid and swath), which tie the remote sensing data and geographic location together, are defined within the HDF framework. Meanwhile, the structural metadata specifies HDF-EOS file content and structure, that is, the relationship between the geographic information (such as location, time and map projection) and the data itself. The swath data type mainly applies to level 1 and level 2 data products, and the grid data type is mainly used for level 3 and level 4 data products [12, 13].

Another one is that the EOSDIS establishes a unified time-space metadata framework. The EOSDIS provides a common exchange platform for the data and information among DAACs by the EOS Clearing House (ECHO). Within this common metadata framework, the ECHO provides EOS data registry and services registry. No matter where the data is physically stored, users can find it by a unified way. In terms of data search, the ECHO adopts the web-based Warehouse Inventory Search Tool (WIST) to provide cross-discipline search services for one-stop shopping [14].

The last one is that the EOSDIS attempts to achieve the automated online storage management with Linux system's own characteristics. In order to increase the data interoperability and usability and improve data access and processing while decreasing operation costs, the NASA implemented a simple, scalable, script-based science product archive (S4PA) data management system to replace the former ECS by reusing the in-house development in 2006. The S4PA makes use of Linux hierarchical directories to organize and manage EOS data files for replacing commercial database systems. The files are stored in the hierarchical directories on disk arrays, and each directory corresponds to a trigger so that the command can start the work tasks. Therefore, all data connected to FTP servers can be stored in an automated online way. The top layer of the hierarchical data directory is the name of the data group, the lower layer is the name of the data set, and the data files are stored in different directories according to their observing time [15].

2.2 Remote sensing data storage and management technologies of World Wind

Aiming at the online storage, management and access methods for remote sensing data, World Wind, a three-dimensional virtual earth was developed by NASA. In addition, it was developed and distributed under an open source agreement.

2.2.1 Data storage and organization model of World Wind

World Wind adopts multi-resolution tile overlay based on equal-angle intervals of the latitude and longitude grid to store and organize remote sensing data, as shown in Figure 2. At the coarsest level, World Wind divides the sphere into 10×5 grids and each tile covers 36°×36°. Then it subdivides each tile at the upper level into four tiles and each tile covers 18°×18°. Following this way, World Wind subdivides the Earth's surface hierarchically. In the Plate Careé projection, each image tile has a fixed size of 512×512 pixels, and is stored and organized to the corresponding level of geographic grid. The numbers of the row and column of the geographic grid tile name the filename of the image tile. Every image tile file is organized and managed according to the hierarchical structure of "Data Set\Level\Row\Row_Column. Image Format" [16, 17]. The characteristics of storage and organization model of World Wind lie in storing and managing remote sensing data according to its geo-spatial region.

2.2.2 System architecture of World Wind

In the aspect of the system architecture, World Wind adopts the server cluster storage to store and distribute remote sensing data. As shown in Figure 3, the root server is responsible for specifying the kind of data set, the geographic

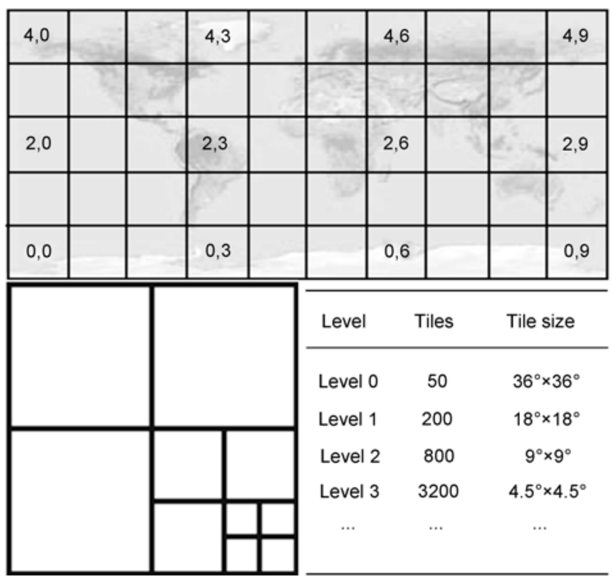

Figure 2 Tile storage and organization model of World Wind.

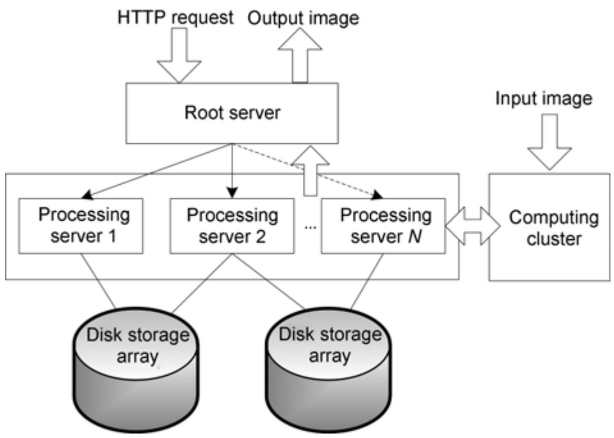

Figure 3 Schematic diagram of the system architecture of World Wind.

location and range according to a HTTP request, and sending the request to an appropriate processing server. Facing a large number of simultaneous access requests, World Wind adopts the on-demand data processing mechanism and the strategy of multi-threaded processing pool. The processing server firstly checks whether there is the requested data in the cached results, if not, then computes and deals with the original data files. Every processing server adopts a single threaded response pipeline for all requests that lead to retrieving cached data products, and throws all other requests into a multi-threaded processing pool [17].

2.3 Remote sensing data storage and management technologies of Google Earth and Google Maps

Google Earth, an image Earth system launched in June 2005, shows the technological advantages of a new generation management platform for remote sensing image data, and provides the most efficient three-dimensional view. Google Maps mainly provides the vector maps, satellite images and 3D panoramic images.

2.3.1 Data storage and management model of Google Maps

Google Maps adopts the quadtree-based tile overlay technology to store and organize remote sensing image data, and the subdivision method of each tile is as shown in Figure 4. At the coarsest level, Google maps adopts one tile centered at longitude 0° and latitude 0° to represent the whole sphere. Then each upper tile as a parent node of the quadtree subdivides the Earth's surface hierarchically. In the Spherical Web Mercator projection, each image tile is organized with reference to the pyramid model. The system adopts the number of the column of the geographic grid to name the filename of each image tile file, and the tile file is organized according to the hierarchical structure of "Data Set\Level\Row\Column. Image Format". The image format adopts JPEG and PNG [18].

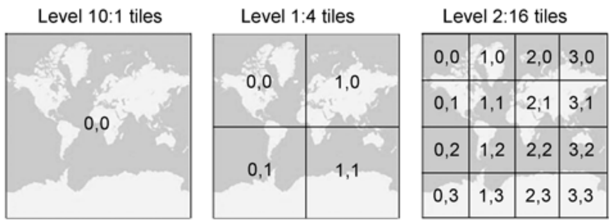

Figure 4 Tile storage and organization model of Google Maps.

2.3.2 Data storage and management model of Google Earth

Google Earth adopts the multi-resolution image overlay technology to organize remote sensing image data. The system overlays image tiles with different resolutions in the WGS84 geographic coordinate reference system. Each image tile is not required to be in a specific tile size, but the linear dimension of square tiles must be an integer power of two between 256 and 2048 pixels. Each image tile in the hierarchical structure is accompanied by an individual KML file that specifics its relative path, geographic range, zoom level, and the corresponding relationship between the upper and the lower. A master KML file references the tile set. The system adopts the number of the column of geographic grid tile to name the filenames of the image tile file and corresponding KML file, and organizes them according to the hierarchical structure of "Data Set\Level\Row\Column. Image Format". The image format mainly adopts JPEG, PNG and GeoTIFF [18, 19].

2.3.3 Cluster storage technology of Google Earth

In the aspect of remote sensing data storage and management, Google Earth, Google Maps, and Google Earth Builder all rely on the Google cloud computing technology to achieve the online storage and application for massive remote sensing data. The basic architecture of Goolge cloud-computing system is mainly composed of GFS (a scalable distributed file system), Bigtable (a distributed storage system for structured data), MapReduce (a simplified data processing model on large clusters), and Chubby (a highly available and persistent distributed lock service), as shown in Figure 5. The four parts are independent of each other and closely integrated. Among them, GFS is at the bottom of all the core technologies and responsible for remote sensing data file storage [20–22].

In the aspect of the system management and scheduling, Google Earth mainly adopts Bigtable running on GFS to form a virtual distributed index database for managing global remote sensing data so that it can quickly find the data of different spatial ranges and resolutions. Figure 6 shows the system scheduling and data operation of the Bigtable cluster.

The Bigtable cluster adopts one table distributed across hundreds of tablet servers for indexing data stored in GFS. The master server is mainly responsible for scheduling

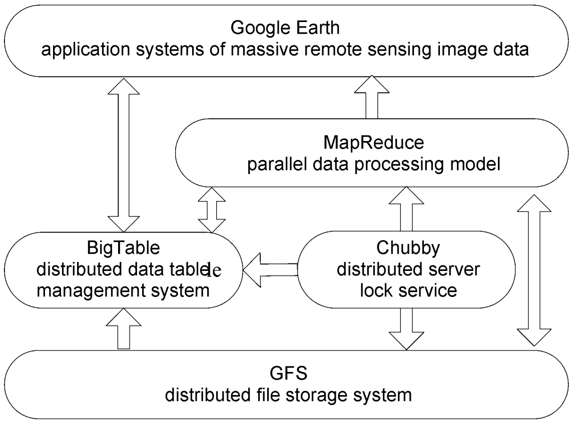

Figure 5 Cluster storage and management architecture of Google Earth.

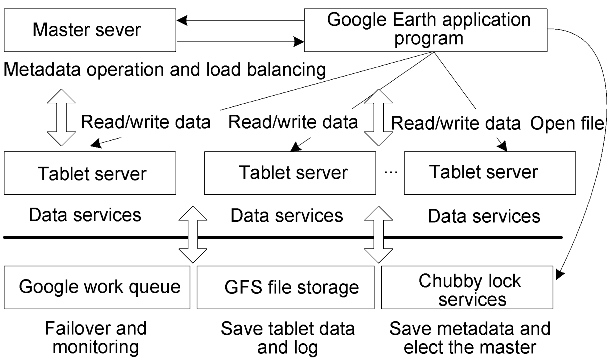

Figure 6 System scheduling and data operation of Google Earth.

tablet servers, and clients can directly interact with tablet servers for reading and writing the data. When external users interact with Google Earth, the system adopts the Ajax-based asynchronous network transfer mechanism to separate the user interaction with the Ajax engine from the Ajax interaction with the servers. When a user makes an operation, the Ajax engine can work out the new image tiles that need to be loaded by certain algorithms, and sends request to the servers in a multi-threaded asynchronous way. Then, by the in-memory strategy, Bigtable rapidly processes a large number of requests in the lower response delay, and returns image tiles to the clients. Finally, the Ajax engine seamlessly merges the image data of the user interface without refreshing. In addition, a caching mechanism is implanted in the user's browser, and the image tiles that have been obtained by the user can be directly used again without sending requests to the servers the next time. Thereby, the users can carry out their various actions with almost no wait so that the system can meet millions, even tens of millions of simultaneous access requests every day [22–25].

2.3.4 Advantages of Google Earth cluster storage system

One is the separation between the control flow and the data flow. Both GFS and Bigtable systems adopt the central server model to form a unified logical namespace and distributed configuration management of data servers.

The other is the parallel storage of data chunks. The system divides each data file into fixed-size chunks, and the default of each data chunk is 64 MB. All data chunks as Linux files are stored on multiple data servers for improving I/O parallelism of the overall system.

2.3.5 Disadvantages of Google Earth cluster storage system

Google Earth organizes multi-resolution remote sensing data along the vertical layers, but along the horizontal direction, the system does not consider the organization issue of multi-source remote sensing data at the same layer.

The system adopts the strategy of "space for time" for organizing and storing the data of the same spatial region and different resolutions on a large number of different storage nodes, but the system architecture requires that all storage nodes and services run all the time while it provides data services. As a result, the system maintenance and power consumption is huge.

2.4 Remote sensing data storage and management technologies of Bing Maps

Bing Maps, formerly Microsoft Virtual Earth, is an online mapping service platform released by Microsoft, and provides vector maps, satellite images and 3D panoramic images.

2.4.1 Data storage and organization model of Bing Maps

Bing Maps adopts the quadtree-based custom tile layers to storage and organize remote sensing data, and Figure 7 shows the subdivision method of image tiles [26]. At the coarsest level, the system represents the Earth's surface with 2×2 grids, and the common corner of these four tiles is located at longitude 0° and latitude 0°. Then each upper tile as a parent node of the quadtree subdivides the Earth's surface hierarchically. In the Spherical Web Mercator projection, each fixed-size image tile corresponds to a global grid. The size of the image tile is 256 × 256 pixels, its format adopts JPGE or PNG, and its filename is the number of the

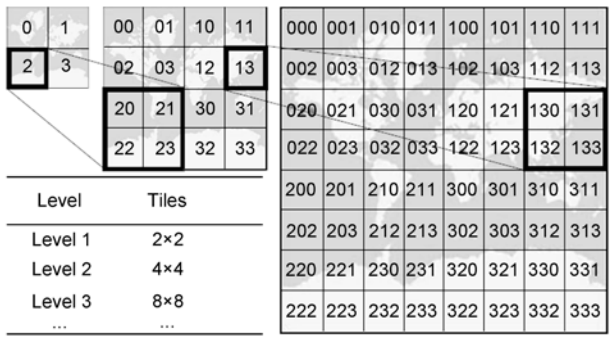

Figure 7 Custom tile layers of Bing Maps.

column of the corresponding global grid.

2.4.2 Cluster storage technology of Bing Maps

Bing Maps mainly relies on distributed cluster storage systems and the cloud-computing platform (Windows Azure Platform) of Microsoft data centers, and the overall structure is as shown in Figure 8 [27, 28]. The Windows Azure Platform consists of three main components: Windows Azure, SQL Azure, and Azure AppFabric. Windows Azure as the operating system in the cloud replicates each data file three times, and stores each image tile as Binary Large Object in its blobs. SQL Azure, which is a relational database service built on SQL Server technologies, is responsible for relational data storage, data access, and management components of the automatic configuration and load balancing. It provides quick data index and scheduling response for a large number of user access requests. Net Services of the platform provide the basic architecture of local and cloud applications for supporting cross-language, cross-platform, cross-protocol interoperability. When Bing Maps interacts with the users, Bing Maps adopts the Silverlight-based content delivery network to deliver image tiles. When a user requests a map, the system sends that request to the nearest content delivery network node to compile image tiles and sends back for quick map rendering. In addition, each of the image tiles is cached across the content delivery network at run time.

2.5 Remote sensing data storage and management technologies of Microsoft TerraServer

TerraServer is one of the most popular online atlases, and provides high-resolution satellite, aerial, and topographic images via the Internet. It stores and manages the data according to the Earth projection regions.

2.5.1 Data storage and organization method of TerraServer

TerraServer adopts the UTM projection that divides the Earth into sixty zones from latitude 84°N to latitude 80°S by longitude interval 6°, and the United States occupies 10 zones, as shown in Figure 9. Then the system stores USGS image data according to the data theme and UTM zones [29–31].

First, image data is stored as fixed-size image tiles. An image tile is stored within a column of SQL Server database, its size is 200 × 200 pixels, and its format adopts JPEG, GIF or TIFF.

Second, an image scene organizes image tiles. A scene is a logical mosaic formed by all image tiles that belong to a single data theme, and corresponds to a UTM zone. A single database can contain one or more scenes. Since each scene is a two-dimensional coordinate reference system, the system can directly address any image tile by the six parameters, namely the UTM zone, data theme, resolution level, and relative position of *X* and *Y* coordinates in the scene.

2.5.2 Physical storage architecture of TerraServer

In 2000, TerraServer adopted the storage area network and Microsoft cluster services to establish the SAN-Cluster storage architecture, as shown in Figure 10(a). The disk array in the SAN is divided into three databases and each database is responsible for storing the data from the same theme. In 2003, in order to increase the online storage capacity while reducing the system operation costs, the TerraServer Brick architecture built by low-cost SATA disks replaced the SAN Cluster, as shown in Figure 10(b). Although the physical architecture has changed, the method of remote sensing data storage and management is the same [31–33].

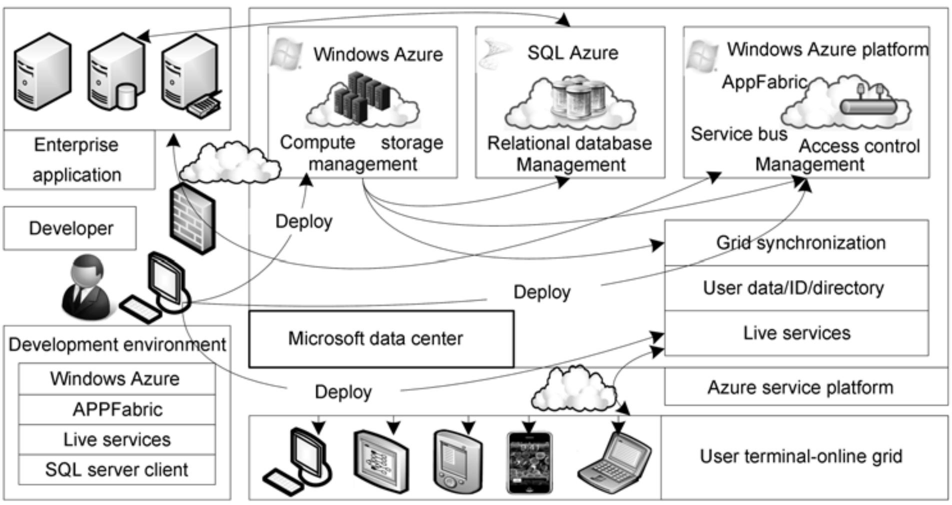

Figure 8 Schematic diagram of cloud computing platform of Bing Maps.

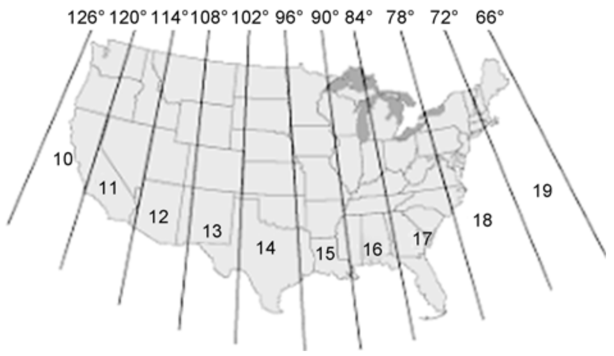

Figure 9 UTM zone division of Microsoft TerraServer.

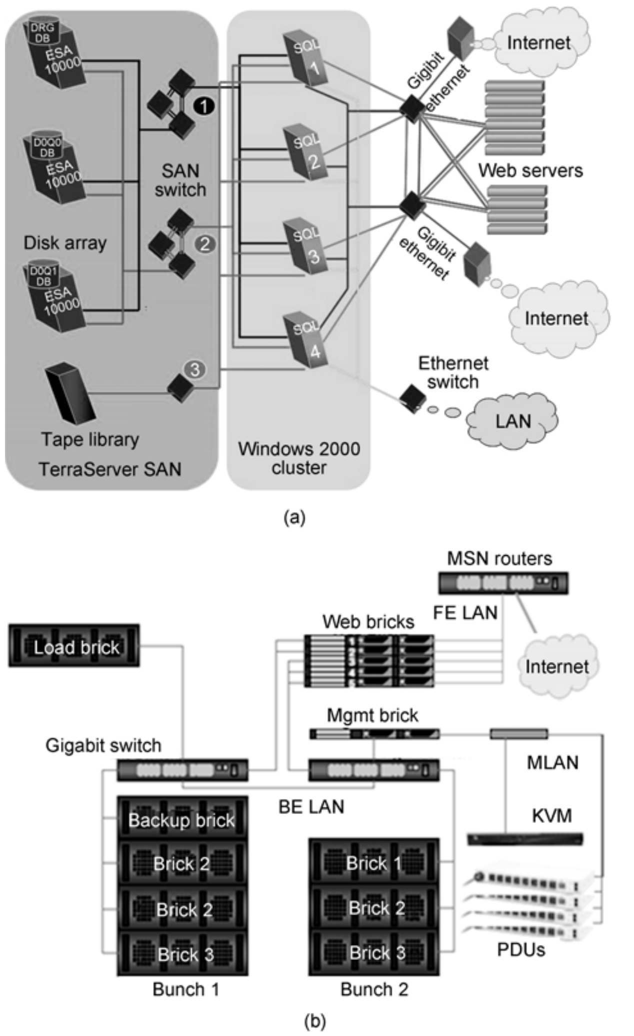

Figure 10 Physical storage architecture of Microsoft TerraServer. (a) SAN Cluster storage architecture; (b) TerraServer Bricks storage architecture.

2.6 ESA data centers

For massive remote sensing data storage and management, the European Space Agency (ESA) adopts a kind of distributed storage architecture with a single multi-mission catalogue, that is, ESA takes the European Space Research Institute (ESRIN) as the reference centre and forms multiple data archive centers [34].

In the aspect of the data storage method, the system adopts a hierarchical storage management mode. The online data is stored in the disk-based SAN and Cluster; the near-line data is archived by the tape-base storage system.

In the aspect of the data management, the system adopts the commercial database to manage remote sensing data by the satellite name and data time. Besides, ESA data storage and management mainly embodies the following two advantages.

One lies in the idea and strategy of the full data sharing and long-term preservation. In respect of massive satellite data storage and management, ESA is more inclined to seek a kind of grid-based resource-sharing model. It is by means of planning a ground high-speed network to connect and integrate the various distributed resources for sharing all kinds of remote sensing data and remote sensing ground facilities within the European Union. For example, ESA has established the Grid Processing on Demand (G-POD) for Earth observation applications and the Ground European Network for Earth Science Interoperations-Digital Repositories (GENESI-DR), so that it can acquire, store, manage, access PB-level remote sensing data [35, 36].

The other is to establish the Standard Archive Format forEurope (SAFE). For the multi-source remote sensing data, a unified standard is the basis of information interoperability and sharing. The SAFE is designed to act as a common format for archiving and conveying data within ESA archiving facilities. In addition, the abstraction models of SAFE include the information model, logical model and physical model [36].

2.7 Cluster management technologies of Earth Simulator

Earth Simulator built in 2002 is an integrated computing and storage environment for simulating the Earth's natural and geographical processes. Since the online power consumption and maintenance costs too much, the processor nodes were reduced from 640 to 160 in 2009, thus the power consumption reduced by 20% to 30%. However, the system storage and computing performance increases two to 3.5 times by upgrading the hardware and software of processor nodes [37]. Therefore, the energy consumption problem of the large-scale data computing and storage systems is worthy of attention. For the massive data storage and management, it is worth learning from Earth Simulator is the grid partition of processor nodes and the cluster system by the parallel scheduling mechanism.

2.7.1 Geographic grid partition of processor nodes

While simulating the atmosphere and ocean models, Earth Simulator generally adopts quasi-uniform spherical grids (the cube grid, icosahedron grid, latitude and longitude grid or yin yang grid) to divide the Earth's surface in a certain scale, as shown in Figure 11, and each processor node is corresponding to a logical geographic grid [38, 39]. Thus, each processor node is responsible for computing the data that belongs to the geographic grid. In a sense, the idea of partitioning all processor nodes according to geographic grids can produce a storage and management strategy, by which each storage node may be responsible for storing and managing remote sensing data that belongs to the same geographic grid according to the geospatial regional feature of the data.

2.7.2 Parallel scheduling mechanism of Earth Simulator

For massive remote sensing data cluster storage, the hierarchical parallelizing management system of Earth Simulator is helpful to improve remote sensing data processing, storage and management [40, 41].

The first level is the parallel programming in a processor that consists of eight sets of vector units. This way can produce a parallel programming for storing remote sensing data within a single disk or disk array.

The second level is the parallel programming in a node that consists of eight arithmetic processors. This way can produce a parallel programming for storing remote sensing data within a single storage node.

The third level is the parallel programming among distributed nodes. The operating system manages Earth Simulator as a two-level cluster system. Sixteen processor nodes constitute a Small Cluster (S-Cluster), which may share in the original workload for a node. Multiple S-Clusters can share in medium and large-scale batch processing. This way groups 640 processor nodes into 40 S-Clusters. Each S-Cluster has a cluster control station (CCS) to monitor the node operation and power situation. Moreover, a super-cluster control station (SCCS) provides a single system image for integrating and coordinating all CCSs. For a remote sensing data storage and management system, if referring to the cluster management mechanism of Earth Simulator, the system may group one or multiple storage nodes to correspond to a geospatial region, and control and deploy all storage nodes on demand.

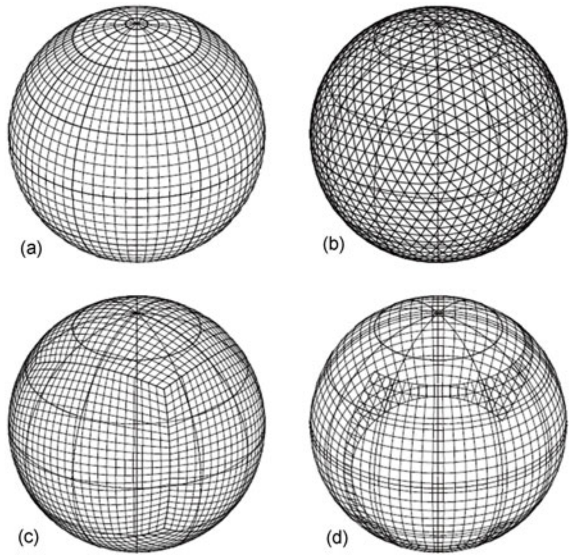

Figure 11 Four quasi-uniform spherical grids for atmosphere models. (a) Latitude and Longitude Grid; (b) Icosahedron Grid; (c) Cube Grid; (d) Yin Yang Grid.

2.8 Image storage management technologies of GeoEye

GeoEye is the world's largest commercial remote sensing company and delivers high-resolution satellite imagery and products. According to the statistics by GeoEye in 2010, Geoeye-1 and IKONOS satellite data has exceeded 420 million square kilometers; the data that needs to be stored is dramatically increasing every day. How to store and manage massive remote sensing data more efficiently and orderly is also a great challenge for GeoEye [42].

In the aspect of the long-term preservation and synchronous sharing of remote sensing data, GeoEye initially adopted its own application software to maintain the hierarchical storage and management and transfer the data between the disk pool and the tape library. In order to simplify this management and enhance data interoperability and system scalability, Geoeye implemented the StroNext data management system as a glue to bind the SGI-based data ingest system and the windows-based image production system. Thus, the synchronous sharing of a single data set between different systems is achieved [43].

3 Domestic remote data storage and management technologies

3.1 Remote sensing data storage and management technologies of Map World

Map World, an Internet-based public geographic information service platform led by the State Bureau of Surveying and Mapping (SBSM) in China, formally launched on January 18, 2011. It will play an important role in the construction of the public service platform in China. Based on the software platform of GeoSurf and GeoGlobe by Wuhan University and WUDA GEO [44], Map World provides two-dimensional and three-dimensional view based on the vector map and satellite imagery and measurement services of distance and area for users. Its main design idea is that the national geographic information and data resources are logically integrated and the data is physically stored in a distributed way. Thus, it can form a kind of information sharing mechanism, by which various departments can participate in the construction to achieve linkage update and collaborative services.

In the aspect of data features, the total amount of data is about 30 TB (the total number of tiles is about 30 million), the data is published according to different application levels for users, and the system provides the comprehensive utilization and online service of multi-scale and multi-type geographic information resources.

In the aspect of data storage organization, Map World adopts multi-resolution pyramid tile technology. In the China Geodetic Coordinate System 2000 (CGCS2000), the system organizes image tiles hierarchically according to global subdivision technology, and the scale of each level (i.e., ground resolution of each tile at a certain level) is fixed. As shown in Figure 12, the subdivision of tiles starts from longitude 180°W and latitude 90°N, and increases along the east and the south, respectively. After the first level, the upper tile as the parent node of the quadtree subdivides the Earth's surface hierarchically. Considering the efficiency of the transmission and scheduling, each image tile has a fixed size of 256 × 256 pixels. The data format adopts PNG and JPG.

In the aspect of data management, Map World adopts a mixed mode of the commercial database and files to support the database storage and large file storage. The system establishes a time-space integration index based on the Morton coding to provide high-performance access interface. In the aspect of data service model, the system adopts multi-server cluster system to meet a large-scale concurrent access requests by the collaborative scheduling and load balancing.

In the aspect of data access mode, Map World provides the external portal and service interfaces based on the common HTTP protocol. By deploying eight map servers in the server cluster, it can provide 24-hour online services and meet the access requests of the 10 million pages per day.

3.2 Remote sensing data storage and management technologies of the CRESDA

The CRESDA (China Centre for Resources Satellite Data and Application) is responsible for long-term archiving preservation of all remote sensing data from land observation satellites (such as the CBERS-01/02/02B and HJ-1A/1B) and user services [45, 46].

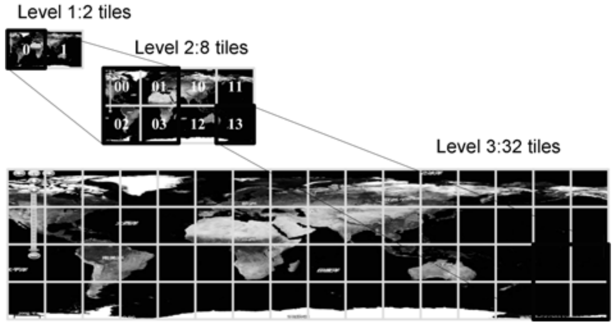

Figure 12 Tile storage and organization model of Map World.

In the aspect of storage architecture, the satellite ground system adopts a kind of centralized storage and distributed processing management architecture, that is, the distributed system is composed of the PC server cluster and SAN storage system. The online data is stored with the disk array, the near-line data is stored with the tape library, and the off-line data is stored on the tape.

In the aspect of the network environment, the internal network adopts the Gigabit switch network, and the external adopts the fast broadband. The internal and external networks are isolated with a gateway.

In the aspect of the data management, the data products are stored and organized by the scene, the metadata is managed by the commercial database system (such as Oracle), and the data product format adopts GeoTIIF. In addition, the system adopts a web-based data access and provides level 2 products for customers.

3.3 Remote sensing data storage and management technologies of NSMC

The Satellite Data Archive Center (SDAC) of the NSMC (National Satellite Meteorological Centre) is one of the largest remote sensing data storage systems in China, and is responsible for storing and managing the data from the FY-1/2/3 series of satellites. For the construction of next-generation data center, the NSMC is in an effort to promote a data storage and management center that is of automation, high reliability, seamless scalability and low consumption [47–51].

In the aspect of the storage architecture, the system adopts the server cluster and SAN storage. The online data is stored with the disk array of 364 TB, the near-line data is stored with the tape library of 2.5 PB, and the off-line data is stored on the tape.

In the aspect of the network layout, the Infiniband and Gigabit Ethernet Fiber are laid out among several sets of servers to achieve the forward pass among various memories and improve data transfer and processing.

For the data division, the meteorological data from the polar orbital satellites is divided regionally by referring to the satellite transit track as a unit. As shown in Figure 13, the Chinese mainland and the surrounding areas are divided into 62 grids and each grid size is 5° × 5°. The data from the geostationary satellites is divided regionally by taking the equator as the dividing line, that is, the scan line 1146 is as the dividing line to divide the northern and southern hemisphere data.

In the aspect of the data storage management, the system adopts the SQL Server and Sybase enterprise databases to manage the meteorological data. The system organizes the data according to the satellite strip and catalogues the data in accordance with the classification of the satellite and time. The data product is a storage in HDF format. In addition,

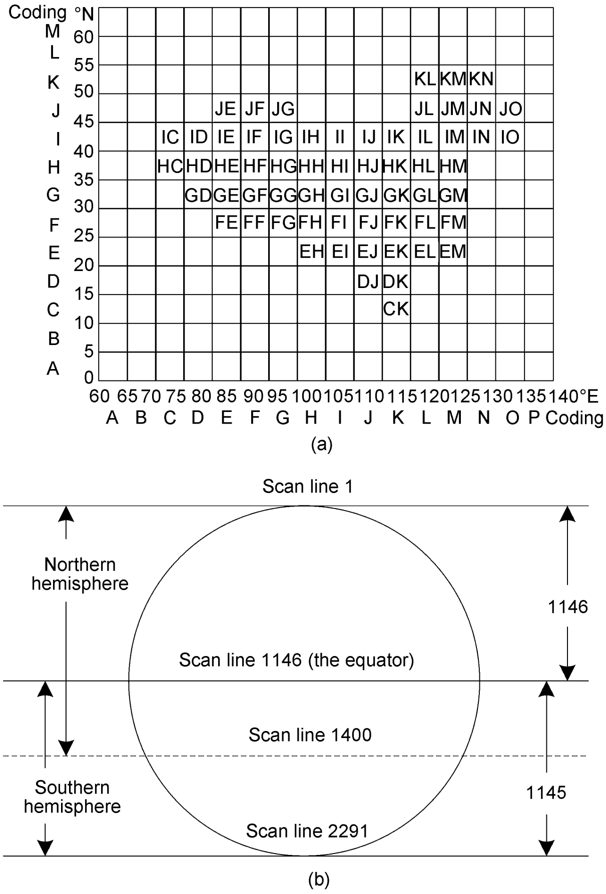

Figure 13 Data division methods for meteorological satellites. (a) Data division for polar orbital satellites; (b) data division for geostationary satellites.

the system supports an operational state of 24 × 7 (hours × days) and provides a Web-based data access.

In the aspect of the project construction of data storage system, the NSMC also faces the pressure of the heavy energy consumption, such as the electricity bill more than three million Yuan in 2008. Meanwhile, the cooling problem of the data center is also quite severe, and more air conditioning cabinets put pressure on the room space. Therefore, the system energy problem is the one that should be considered for massive remote sensing data storage and management.

3.4 Remote sensing data storage and management technologies of the NSOAS

The ground application system of the NSOAS (National Satellite Ocean Application Service) is responsible for storing and managing remote sensing data from the ocean satellites, such as the raw data and level 0–level 3 data products from the HY-1A/1B satellites, the raw data from the NOAA satellites, as well as the EOS-MODIS satellites [52, 53].

In the aspect of the storage architecture, the storage system adopts the three-level NAS storage system connected by the Gigabit Ethernet. The first level adopts the fiber disk array for online data, the second level adopts the large-capacity SATA disk array for near-line data, and the third level adopts the modular tape library system and the DVD recorder system for data backup. In the aspect of the data management, the system adopts the commercial database management (such as Oracle), in which the satellite and file names are set as the primary keys.

4 Comprehensive analysis of the remote sensing data storage and management technologies at home and abroad

The domestic and foreign storage and management technologies for massive remote sensing data are compared comprehensively, as shown in Table 1.

According to the physical storage architecture, the above data centers or systems may be classified into three categories. One includes the NASA EOS, Google Maps, Google Earth, Bing Maps, ESA, and Map World. They belong to the geographically distributed server clusters. This storage architecture of logically centralized storage and physically distributed storage mainly applies to the national level of large-scale data storage center, and solves the conflict between the existing different storage systems and the unified storage in the centralized way. Another one includes World Wind, TerraServer, GeoEye, the CCRSDA, the NSMC, and the NSOAS. They belong to the geographically centralized server clusters. This storage architecture mainly applies to the departmental level of massive remote sensing data storage center. Unlike the above two categories, Earth Simulator belongs to the computing cluster. In terms of the data storage pool, the three-level storage architecture, which are composed of online, near-line and offline, is an effective solution to the conflict between the data access speed and the storage capacity. However, there are also the data scheduling problems in the actual applications. For example, the online storage resources are limited so that it is difficult to achieve the dynamic scalability or flexible configuration in accordance with geospatial characteristics to meet the rapid growth of remote sensing data. Since a large amount of data is in the near-line and off-line states, the data transfer costs much time, and it is not convenient to directly access the data in a real-time online way. In addition, the cloud-computing model is one of the most promising solutions to massive data storage and processing, as well as the cloud storage based on the cloud-computing model. However, for the large-scale storage management of massive remote sensing data, especially the high-resolution remote sensing data, both the cloud-computing model and the cloud storage cause huge amounts of redundant backup of the online data and do not consider the geospatial distribution feature of remote sensing data. To a certain extent, this way is hardly conducive to the regional computing and process-

Table 1 Comprehensive analysis of the remote sensing data storage and management technologies at home and abroad

Storage center or system	Physical storage architecture	Data storage organization	Data format	Data storage management
NASA EOS	Distributed server cluster storage and three-level storage	Earth science disciplines and satellite orbital strip or scene	HDF-EOS	Commercial database and Linux file system
World Wind	Centralized server cluster storage	Tile layer based on the spherical grid and the Plate Careé projection	512×512 pixels, any image format (JPGE, PNG, DDS)	Distributed file system
Google Maps	Distributed server cluster storage and cloud computing	Quadtree-based tile layer and the Mercator projection	256×256 pixels (JPEG or PNG)	BigTable and GFS
Google Earth	Distributed server cluster storage and cloud computing	Tile overlay in the WGS84 and the Plate Careé projection	An factor of 2 between 256 and 2048 pixels (JPEG, PNG or GeoTIFF)	BigTable and GFS
Bing Maps	Distributed server cluster storage and cloud computing	Quadtree-based tile layer and the Mercator projection	512×512 pixels (JPGE or PNG)	Windows Azure and SQL Azure
Microsoft TerraServer	Centralized server cluster storage	UTM zone division and data tile	200×200 pixels (JPEG, GIF or TIFF)	Blob-based SQL Server databaser
ESA	Distributed server cluster storage and three-level storage	Satellite orbital strip or scene	CEOS, HDF, GeoTIFF, and so on	Commercial database and file
Earth Simulator	Computing cluster	Computing data division according to the spherical grid	NetCDF	Parallel file system
GeoEye	Centralized SAN and Cluster	Satellite orbital strip or scene	TIFF, NITF, GeoTIFF, and so on	SAN file system
Map World	Distributed server cluster storage	Pyramid tile based on equal intervals of the latitude and longitude（CGCS2000）	256×256 pixels (JPEG or PNG)	Commercial database and file
CCRSDA	Centralized server cluster storage and three-level storage	Ground scene grid	GeoTIFF	Commercial database (Oracle) and file
NSMC	Centralized server cluster storage and three-level storage	Satellite orbital strip	HDF	Commercial database (Oracle /Sybase) and file
NSOAS	NAS-based three-level storage	Satellite orbital strip	HDF	Commercial database (Oracle) and file

ing of remote sensing data. Therefore, the existing storage systems should not only consider all Earth data stored, but also need to establish a global-scale data storage model, so that it can combine this model with the regional characteristics and lifecycle features of remote sensing data to efficiently manage and schedule massive remote sensing Data.

According to the data storage organization, the thirteen data systems may also be classified into three categories. One mainly includes World Wind, Google Maps, Google Earth, Bing Maps, and Map World. They belong to the multi-resolution pyramid tile model based on the discrete global grid. This model mainly applies to the seamless organization and visualization view of remote sensing data, and solves the imagery-based real-world presentation. However, among this category of data storage systems, there is a lack of managing multi-source remote sensing data along the horizontal direction. Another one, like TerraServer, also belongs to the image tile model, but it is only a mosaic of a projection zone and does not establish multi-scale image pyramid along the vertical layers, as well as multi-source remote sensing data. In a sense, Earth Simulator also establishes the grid tile model when it organizes the remote sensing data in accordance with the spherical grid. The last category includes GeoEye, NASA EOS, the CCRSDA, the NSMC, and the NSOAS. They belong to the satellite orbit strip or scene model based on the time-space record system, in which the raw orbital data is stored in accordance with the received time order. However, in this traditional record system, there is lack of a unified division standard for various data products among different production departments, and the identification of data products has not the geospatial meaning. Moreover, the various multi-source, multi-scale and multi-temporal data that is in the same area lacks a direct relationship with the geospatial scale and location. Since the multi-source data in the same area is stored on different orbital strips, it is a very time-consuming work to integrate the multi-source and multi-temporal data from different data departments. Therefore, this record system also brings much inconvenience in the aspect of the data management and integration. In contrast, the model that adopts the discrete global grid to cover the Earth’s surface can efficiently represent a certain region from the centimeter size to the whole Earth by means of a series of seamless non-overlapping cells of the multi-scale hierarchical structure. Moreover, this model will be helpful to combine the geospatial characteristics of the data with the regional characteristics of the global cells, and establish the direct relationship between the practical applications of the data and the geospatial scale and location. Ultimately, the geospatial location identification and geospatial object identification based on this global subdivision model can be established to provide the global geospatial storage reference and the data identification of the geospatial meaning.

According to the data format of the data storage management, the thirteen data systems may be classified into two categories. One includes World Wind, Google Maps, Google Earth, Bing Maps, TerraServer, and Map World. They belong to the fixed-pixel image tile, and it mainly applies to the quick display of the pyramid images. The other includes NASA EOS, GeoEye, ESA, the CCRSDA, the NSMC, and the NSOAS. They belong to the data product format based on the satellite orbit, and it mainly applies to the business product management.

According to the mode of the data storage and management, the thirteen data centers or systems may be classified into three categories. One includes NASA EOS, World Wind, Google Maps, Google Earth, GeoEye, and Earth Simulator. They belong to the file-based distributed file system. Another one includes TerraServer and Bing Maps, and belongs to the BLOB-based relational database management. The last one includes ESA, Map World, the CCRSDA, the NSMC, and the NSOAS. They belong to the mixed mode of the file and the commercial relational database.

In terms of the system maintenance and energy consumption, since the existing three-level storage architecture needs both online and near-line storage nodes or disk arrays to run all the time while providing the data services for users, its energy consumption is huge. Moreover, for the ultra-large-scale storage system of tens of PB-level storage capacity, its storage nodes are generally up to thousands. When the storage scale increases, the energy consumption comes along with it. Therefore, it is needful to establish a reasonable storage and organization model and the corresponding storage architecture to correlate the remote sensing data with the storage resources. According to regional characteristics of the user access, this model can form a kind of on-demand scheduling mechanism to support system maintenance and efficiently cut down energy consumption. For example, when the data that belongs to a certain region is on demand, the storage resources of that region is online, otherwise, shutdown or on standby. Therefore, aiming at the storage problem of the massive remote sensing data, it is worth thinking and researching what kind of data organization and storage mode is appropriate to establish a unified geospatial storage reference and manage the PB-level remote sensing data more efficiently. In addition, this mode should be able to improve the comprehensive management capabilities (such as the massive remote sensing data integration, sharing, quick access and distribution) fundamentally and achieve the on-demand online services and applications while reducing the energy consumption efficiently.

5 Conclusion and prospect

In this paper, the characteristics and advantages of thirteen data storage systems were analyzed systematically from the aspects of the storage architecture and the storage organization model.

In view of the development of the 3G, the next-generation Internet, the cloud computing and the cloud storage, a viewpoint can be deduced that the distributed cluster storage will be the trend of massive data storage technologies and the "one-stop service" mode of remote sensing information will become the mainstream. However, the key point of the storage and management architecture for massive remote sensing data lies in the combination of the global remote sensing data storage model and the modern storage technologies. Thereby, it can form a space-based distributed cluster storage system, in which the system is of global coverage logically, the data is in distributed storage physically and the information is on sharing efficiently. In addition, with the development of the computer technology and the geospatial science, the storage system applied to the remote sensing information field will take on more special feature. The storage system has an integrated storage view for global remote sensing data, a regional division mode of customized and personalized features, a simplified manipulation mode, a flexible configuration for storage resources, a easy-management and low-consumption scheduling mechanism, and so on.

In view of a large number of research results of the surveying and mapping systems and the remote sensing data organization mode in China, the data organization mode in China will not change fundamentally in the present or in a relatively long period. That is, the global remote sensing data is organized with latitude and longitude and the local area or plane data is organized with Gauss projection. Thus, according to China's national conditions, a global subdivision framework, which is on the basis of latitude and longitude grid while taking into account the mapping division and hundred-kilometer grid, is an effective way to achieve a unified storage model for global remote sensing data.

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