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EVOLUTION AND COMPUTING CHALLENGES OF DISTRIBUTED GIS

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Abstract

As a new development based on GIS and distributed computing, Distributed GIS (DGIS) was introduced and propelled by both the demands for GIS in a distributed environment and the advancements of computing technologies. Demanding for new geospatial applications presents new challenges for DGIS, and the solution to overcome the challenges in turn leads to the advancement of DGIS. This article examines two important aspects of DGIS: its applications and the computing challenges. This paper reviews the three stages of evolution in DGIS application development and further examines its relevant computing challenges, such as system performance, user interface, interoperability, data integrity, spatial data mining, and data and system security.

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1. Introduction

As a new development of Geographic Information Systems (GIS) and distributed computing (Figure 1), Distributed GIS (DGIS) is defined as a GIS with its geospatial data and computing resources distributed across a computer network (Yang 2003). The birth and growth of DGIS were sparked from a growing demand for GIS services across computer networks with heterogeneous computing systems (hardware and software) and in different geographic areas. Just as the Internet has revolutionized the way people live and work, DGIS has transformed the application aspects of GIS and is becoming more and more important in our daily life and around the world acting as a media for communicating geospatial information and knowledge (Sui and Goodchild 2001).

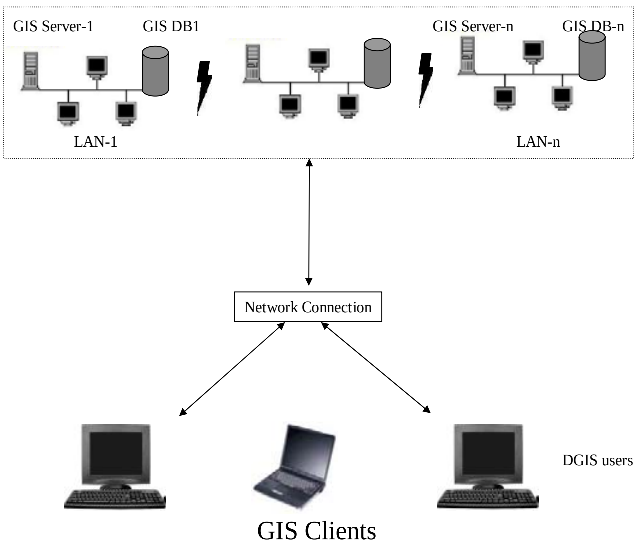

Figure 1: A framework of DGIS architecture

DGIS presents an exciting research and application direction in GIS as it can provide flexible and friendly GIS solutions (Peng and Tsou, 2003). The rapid and broad penetrations of DGIS applications in many aspects of the society call for further research and development on the functionality, scalability, and interoperability of DGIS. These technical aspects of DGIS development are closely related to and dependent upon the evolutions of DGIS applications and computing technology. Application development presents the scientific directions, challenges, and testbeds for DGIS while computing technology dictates the foundation and potential of DGIS. DGIS is examined in this article from two aspects: the evolution of its applications (in section 2) and the computing challenges in advancing this technology (in section 3).

2. The Evolution of DGIS

"New technologies have always been a key driving force in geographic information sciences, as they have in science and society generally." (Goodchild, 2003) DGIS is driven by cutting-edge developments in computing, information, and telecommunication technologies. For example, new generations of operating systems and powerful desktop computing power allow GIS to be operated on our laptops or desktop computers. Similarly, the development and expansion in information technology have transformed the way we process data and manage information/knowledge. The rapid improvement in telecommunication technology provides high-speed networks so that large-volume of data, even multimedia data and other information can be delivered efficiently. Together, these three major technologies affect the pace of DGIS development. In this paper, we will examine DGIS from a historical perspective: The birth of DGIS, the evolution of DGIS applications, and the recent direction in representing the temporal dimension in DGIS applications.

The Birth of DGIS: the origin of DGIS can be traced back to the early stage of computing when users interacted with a mainframe or minicomputer through "dumb" analog terminals. In that setting, multiple users could access the geospatial computing power of a workstation or mainframe/minicomputer from terminals. However, that setup cannot be regarded as real DGIS according to today's standards because the terminals did not support human-computer interface or interactions and processing of geospatial information. The 1993 Xerox webmap server is recognized as the first DGIS application for publishing maps through the Internet (Plewe 1997). Since then, DGIS has been evolved quickly to meet the needs of a variety of applications. Today, DGIS exists in the forms of Internet GIS, Web GIS, Network GIS, and wireless GIS. The functions range from the delivery of static maps to a full suite of on-demand GIS services (Anselin et al., 2004). DGIS has become the system for performing geographic information computing within the Internet, an intranet, an extranet, or the web environment (Jere, 2000). Functionally, it carries on the spirit and application objectives of the original design of the Internet: sharing computation and information through efficient communication across heterogeneous networked platforms. Clearly, DGIS has a kernel objective of delivering geographic data, information, and computing efficiently, universally, timely and securely over the network, wired or wireless. The ongoing evolution in the ways how DGIS applications are implemented continues to drive its rapidly changing development.

The Evolution of DGIS Applications: DGIS has evolved together with the augmentation of computing technology, networking architecture, and GIS applications. It has a much broader group of users and audience than the traditional GIS (Peng, 1999). It has been used in local, regional, national, and international studies, with multiple centers gravitated in the highly developed industrialized countries. Dictated by the inequality of technology access and the development of computing technologies in the global computing environment, DGIS evolution can be delineated into three stages (illustrated in Table 1).

Table 1: Three Stages of DGIS Evolution

DGIS Stage	Network Architectural Components	DGIS Functions	Timeline	Major Providers
Stage I	WAN, Internet, and web server	Static Geospatial data and information dissemination sites	Early 1990s--present	Governmental agencies Academic institutions GIS companies
Stage II	WAN, Internet, GIS server & web server	Geospatial data and info dissemination portal: data distribution with interactive user interface and data processing	Mid 1990s -- present	Major governmental agencies Academic research centers Leading GIS companies
Stage III	New computing infrastructure, such as Grid computing	Interactive on-demand DGIS services: data analysis, modeling, and knowledge systems	Focus of R&D since early 2000s	Major governmental agencies Academic research centers Leading GIS companies

In the first stage, DGIS functioned as an information dissemination method. Distribution of data and information is the focus. It provides static information and does not utilize interactive interface between a server and a client within a network. The server typically displays and shares the data and derives results for an organization to the public. The greatest impact of web-based GIS is that it has revolutionized the access to geospatial data resources (Tang and Selwool, 2002). Everyone who has access to the Internet can participate in this type of data dissemination process. Today, this type of DGIS applications is widely used, particularly so in less-developed countries with limited network access bandwidth.

In the second stage, DGIS acts as a data processing and analysis portal. A cluster offers the utilities that allow users to query and retrieve data, metadata and other information. Many government-sponsored DGISs deliver such GIS services. The Federal Emergency Management Agency (FEMA) has established an all-hazard geospatial data distribution system (Lowe, 2003). The federal government has launched the National Map and the Geospatial One-Stop (GOS) initiatives (USGS, 2001). The Canadian government has also embarked on a national effort in disseminating digital geospatial data (Johnson and Singh, 2003) and the GeoConnections Discovery Portal delivers millions of diverse geospatial data products (http://geodiscover.cgdi.ca/). The European Land Information Services initiative involves eight national information agencies to develop and distribute geospatial land information on the Internet (Guslafsson, 2003). With these applications, users can submit requests to obtain customized geospatial information.

In the third stage, DGIS functions as an integrated data processing, computing, modeling, and knowledge system. It provides rich GIS functionalities to deliver GIS services on demand. Servers geographically dispersed but connected through computer networks work together to share geospatial data, computing infrastructure, and models dynamically in a service-oriented architecture (SOA, Yang and Tao 2005). This type of system has the potential to solve complex natural/environmental and social problems, including responses to hurricanes. It is the most sophisticated and robust stage of DGIS development. In the global economic environment, it has become increasingly important to integrate geospatial information with other socioeconomic databases to come to a better management and decision-making process. Although this stage of DGIS applications is not fully developed yet, many applications show an emerging trend to achieve the aforementioned full DGIS potential. For example, DGIS is used to develop a decision-support system for floodplain and watershed management system (Sugumaran et al., 2000; Dymond et al., 2004). The integration of DGIS and remote sensing technology has been applied to reduce cost and expedite spatial data analysis and display in environmental monitoring and resources management (Tsou, 2004). DGIS is not only used for monitoring and managing existing environment, but also for planning the future environment (Daagicevic and Balram, 2004).

<u>The Representation of Time in DGIS Applications</u>: Just as the representation of time is an important benchmark of GIS development, the evolution of DGIS is also tied partly to the handling of time. The temporal dimension in DGIS applications is reflected through three factors: data source, system functionality, and the nature of the DGIS applications.

Data Source: the temporal extent can only be represented within the time period of the data in DGIS. For example, urban change-detection study can only track the changes over the period covered by the available data. The temporal resolution of an application is dictated by the frequency of data updates. The consistency of temporal resolutions in the existing data dictates the temporal details of a DGIS application. For example, the temporal detail may vary from century, decade, month, day, to real-time.

System Functionality: the evolution of DGIS results in the changes in system functionality, which subsequently affects the treatment of time in DGIS applications. In most of the DGIS applications in the first and second stages, time is profiled as discrete static snapshots. The representation and analysis of time in GIS applications depend on the temporal completeness of the databases. For example, GIS users, who conduct a hazard mapping project in an underdeveloped region and have very limited data sources, can significantly improve the overall temporal resolution and effectiveness of their GIS application by using multiple international sources of data (map and images) through DGIS. In the third stage of DGIS applications, dynamic modeling attests the DGIS feasibility for rapid data processing, analysis, and integration. The real time data stream and temporal animation of geospatial events and phenomena reflect the rapid evolving nature of DGIS. For example, real time studies are used in storm tracking (http://arcweb.esri.com/sc/storm_tracker/index.html).

The Nature of DGIS Application: the treatment of time is affected by the nature of applications. DGIS has evolved to be able to accommodate a wide-spectrum of geospatial applications (Figure 2). Many global environment studies call for monitoring changes at a coarser time scale such as a century or a decadal interval, and many regional studies were conducted in a finer time scale such as annually or a five-year interval. Any natural and human-induced disaster monitoring and management studies -- hurricane, typhoon, earthquake, tsunami, volcanic eruption, landslide, war, and epidemic disease outbreak, law enforcement operations, etc. – requires data with a rapid update cycle and/or in real time to support data analysis and modeling, such as real time flood prediction (Al-Sabhan, et al., 2003).

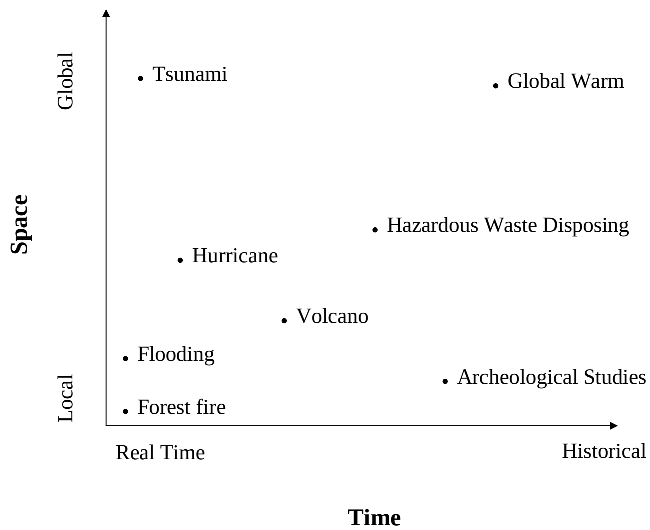

Figure 2: Some examples of DGIS applications in the spatial and temporal dimensions.

3. Computing Challenges in DGIS

There are many challenges ahead before we can develop such a dynamic third-stage DGIS application. For example, the catastrophic earthquake and mega-tsunami combo disaster that occurred on December 26, 2004 in Southeast Asia was a testament of the need for developing a global disaster monitoring and warning system. Ten days after the worst disaster in four decades, discussion about installing the first tsunami warning system in the Indian Ocean was on the agenda of the international summit in Jakarta, Indonesia. Of course, this will be a landmark move toward a global disaster monitoring system. Nevertheless, there is the need for a comprehensive monitoring, warning and response system for all major disasters. Post-disaster relief effort is costly and the irrecoverable loss of lives is immeasurable. For unavoidable natural disasters, early warning systems and pre-disaster planning will generate more societal benefits than merely counting on post-disaster relief and management. DGIS, with the technological bells and whistles, will like play a significant role along this line of effort.

To implement such a global disaster management DGIS is complicated (Fig.3). First, the vast and comprehensive multi-disciplinary and multi-hazard databases need to be developed across a multinational region. Second, the process involves multiplicity of geospatial analyses, which need to be performed in a reliable computing environment. Third, the information distribution infrastructure will be in a multi-layered structure from the virtual headquarter to various administrative levels, such as national, state/provincial/city, and town/county/community levels. The coordination, cooperation, and information integrations present political, technical, and linguistic challenges. Fourth, to maximize the usability of current distributed services and dispatch warning message in an expedited fashion, DGIS has to have the capacity in integrating heterogeneous systems and databases across the world, delivering both spatial and aspatial data, providing interactive interfaces in multi-languages, and performing critical operations in a secure fashion without being sabotaged.

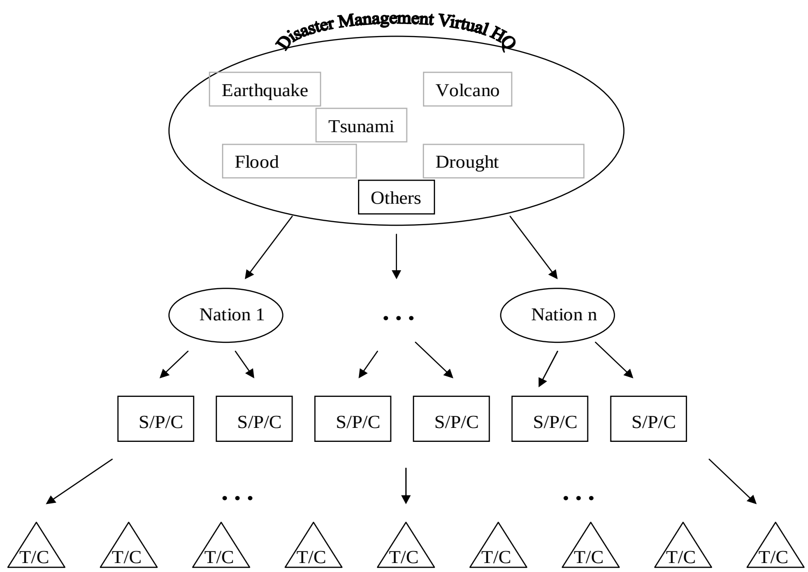

Figure 3: DGIS in global disaster management: data and information on different hazards are integrated and processed in a grid-computing environment at the virtual HQ. The GIS services on hazards, potential warning, and rapid responses can be then efficiently distributed through a multi-layered web structure with the HQ having the outreach capacity of contacting directly any node of the web (potentially impacted areas

This example illustrates that we have various types of challenges to implement a mature and sophisticated DGIS. Within the context of this special issue on DGIS, this article will address only the computing challenges, which may be classified into six major categories: system performance, user interface, interoperability, data integrity, spatial data mining, data and system security (Table 2).

Table 2: Major Computing Challenges in DGIS

Category	**Major Computing Challenges**
System Performance	• Component Affinity/ Multi-task Scheduler • Grid Computing / Data Caching
User Interface	• Client side/Server side • Front end/Middleware/Backend • Encoding/transfer/computing/display language

System Interoperability	• Hardware/Software/Data interoperability • Centralized Computing/Distributed Service strategy
Data Integrity	• Integration: Data type, format, resolution, scale, source • Update: Top-down updating & bottom-up updating
Spatial Data Mining	• Cross-datasets data mining • Data mining for large-scale real world applications • Data Model and structure for data mining in a distributed network environment
Data & System Security	• System Security: security policy & authentication • Data Security: data integrity & encryption • Security Mapping: virtual world vs. real world

System Performance: The core value of DGIS is its distributed computing capacity. DGIS is supported by data-intensive computing at a large scale, where large volumes of data are analyzed and distributed over geographically dispersed locations. Consequently, it is critical to provide prompt responses to users and to have efficient computing-resource scheduling and coordination strategies. In the traditional distributed computing setting, the computing facilities are located together or connected by fast local area networks, such as computing clusters. Within a DGIS, it is also relatively easy to implement the associated loading sharing strategies, such as LSF (Zhou, 1988), dynamic loading sharing (Eager, et al., 1986; Riska, et al., 2002; Chen, et al., 2001; Xiao, et al., 2002), virtual reconfigurations (Chen et al., 2002; Xiao, et al., 2004), and network ram (Xiao, et al., 2000)..

The nature and characteristics of geospatial computing will also affect the performance of the system. For example, if the data and computing components are geographically distributed and are connected mainly via the wide area networks, then current computing strategies, such as LFU and Network RAM, will be of little value for DGIS. Also, existing load sharing and balancing strategies target at managing the intensive CPU workloads only. They are not sufficient and effective in handling the data and intensive I/O workloads in DGIS as the I/O includes not only the local disks I/O, but also the large amount of network I/O. Thus, an efficient task scheduler among the geographically distributed computing facilities is needed to dynamically perform load sharing. For such a purpose, several objectives should be met. First, the data and computing components affinity should be exploited to develop efficient placement strategies. By affinity, it means that the computing components and data should be located close enough to each other. The objective is to reduce as much as possible the relatively low speed data communications. Second, when the data have to be transmitted, the transmission should be performed intelligently so that while waiting for the data inputs, the computing components will not be left idle, but still perform other processes. Third, since DGIS utilizes many distributed facilities, which create challenges in managing local load sharing, the high level parallel computing operations among different computing facilities can be explored to improve the system throughput and reduce the response time to the client requests. Fourth, the client requests often refer to some localities. Data caching can possibly be applied to provide an instantaneous response whenever possible.

The recently emerged grid computing technology, particularly the computing grid, provides a promising platform for DGIS to leverage the distributed computing resources. Evolved from the traditional distributed computing, grid computing presents a promising solution for complex computational problems. It involves coordinating and sharing computing power, applications, data storage, and network resources across dynamic and geographically distributed organizations. To implement DGIS services on the generic general grid infrastructure, however, we need to develop at least the following components. First of all, we need a DGIS resource manager/broker. Its responsibility is to match and pair the service requests with the available resources dynamically, i.e., to achieve the best resource utilization efficiency. Second, a DGIS scheduler is needed to schedule concurrent requests and data transmissions, and it may facilitate task partitioning to improve parallel computation. Third, a dynamic load-balancing tool is desirable. Depending on the task priorities and the queuing length, as well as the available resources, computing jobs may be dynamically partitioned and migrated from one grid node to another so that the overall system performance can be improved. This is also one of the OGC Web Service (phase 3, www.opengis.org) objectives. In practice, this last objective can be achieved by combining the functions of the load-balanced tool with either the resource manager or the scheduler.

User Interface: An effective user interface should be efficient to design and deliver understandable electronic messages (Norman, 1988; Shneiderman, 1998). In DGIS, user interface is the forefront connecting DGIS providers and users. It functions as the invisible arms of DGIS in the virtual world, reaching people in the geographic world. It dictates the efficiency and friendliness of information access and dissemination. It indirectly affects the ways that data and information can be subsequently downloaded, interpreted, and used.

In the pre-windows or graphical user interface (GUI) era, the console design required users to remember long command syntaxes. Later, the GUI design greatly improved human-computer interaction. It allowed users to execute operations by clicking the icons or touching the touchable screen. Gradually, user-interface design heavily relies on knowledge learned from many disciplines, including computer graphics, operating systems, human factors, ergonomics, industrial engineering, cognitive psychology, and the system design of computer science. Since the emergence of the World Wide Web (WWW), a Web portal has been deemed to be a universal Internet-access user interface, where the browser provides a single access point a wide variety of information sources. Due to the characteristics of geospatial databases in DGIS, the user-interface must satisfy the demand from distributed clients with various types of (network) accesses, distributed data and computing facilities, while making these complexities transparent to the users simultaneously. Thus, an interface for a DGIS grid portal should enable users to launch applications that will use the resources and services available in the grid infrastructure. From this perspective, users see the DGIS as a virtual computing system. To develop such a DGIS portal, three layers need to be constructed. The front end receives requests from clients, the middle layer processes requests, and the back end stores data and information. Building such an interface is challenging since it deals with a large number of processes from receiving requests to dispatching the requests to multiple middle processing units and distributed processing centers. The schema of dividing and allocating DGIS functions at either the client side or elsewhere will be a strategic consideration in such circumstances.

Interoperability: Within such a complex, dynamic, and heterogeneous DGIS, interoperability is the key to achieve a stable and smooth integration. Since the inception of GIS, heterogeneity has existed at different levels (Buehler and McKee 1996; Goodchild et al., 1999; Yang, 2000): 1) Different GIS software, such as ArcGIS and GeoMedia, use different data formats, data models, and data processing procedures; 2) Applications developed by different companies use different solution frameworks and approaches; 3) Different communities, such as civil engineering and geography, use different terms for the same feature. This difference in terminologies gradually resulted in the heterogeneity of semantics; 4) Different platforms are used to provide computing support, such as Windows vs. Unix, creating a heterogeneity in computing environment. Because of these different types of heterogeneity, interoperability is one of the most challenging issues in DGIS developing where sharing of information and resources is essential.

To handle the computing heterogeneity problem, systematic research and development are needed to study different levels of heterogeneity. Therefore, in 1994, the OpenGIS Consortium (OGC) and the Federal Geographic Data Committee (FGDC) as well as the International Standards Organization Technical Committee 211 (ISO/TC211) were formed to address the geospatial interoperability issue. With the past 10-year's effort in interoperability research and development and the advancement of information sciences, a series of standards or specifications have been developed by these three organizations.

Developing standards provides benefits to organizations with limited resources before the interoperability issues can be fully addressed (Schuurman, 2002). Web-based solutions around specifications and open source software are tested and proposed to improve system interoperability (Anderson and Moreno-Sanchez, 2003). The use of a suite of products, GML, SVG, WMS/WFS, and Web Services, for encoding, spatial data visualization and data query has been considered as a strategy to offer great potential to achieve the interoperability of DGIS (Peng and Zhang, 2004) and to build distributed geospatial information services (Yang and Tao, 2005). The applications of these specifications or standards have demonstrated many successes in interoperability: 1) the FGDC metadata standards have been widely adopted and integrated with Z39.50 to provide uniform cataloging services for FGDC clearinghouse nodes and have been adopted by many countries to develop the global spatial data infrastructure (http://www.fgdc.gov/clearinghouse/clearinghouse.html); 2) the Web Mapping Service (WMS) has been adopted by FGDC to support mapping interoperability in the past several years; 3) the Web Feature Service (WFS) has been adopted by several FGDC-funded projects to support the sharing of spatial feature data (http://www.fgdc.gov/funding/2004/2004CAP_Projects.pdf); 4) Web Services are integrated with the specifications or standards in developing on-demand data and service discoveries within Geospatial One-Stop (Nebert, 2004) and in building interoperable distributed geospatial information services (Yang and Tao, 2005). These successful examples provide solid foundations to launch the third stage of DGIS applications described above.

However, many challenges remain: 1) among the approximately 20 themes of specifications and standards, only a few have been applied in practical implementations and new standards are under-developed such as the FGDC framework data content standards (http://www.fgdc.gov/RReview/); 2) standards and specifications from different organizations need to be harmonized or consolidated as the metadata standards endorsed by all three organizations (http://www.fgdc.gov/metadata/metadata.html); 3) semantic interoperability is still far from success (Goodchild, 2004); 4) Web Services-based practical interoperability research and development have just started in the past few years after Web Services become practical (Yang and Tao, 2005); 5) with the specifications and standards introduced and the interoperability functions embedded into different software, the performance of DGIS has to be addressed so that interoperable DGISs are not inferior in performance (Yang et al., 2005); 6) with the integration of massive distributed geospatial databases, computationally intensive operations should be performed in a timely fashion within different servers and clients (Anselin et al., 2004; Yang et al., 2004).

Data integrity: Data integration and update management present another persistent but an increasing difficult challenge. First, this general challenge is related to the history of data sources. Data heterogeneity existed before the digital age and way before the emergence of system or software heterogeneities. Second, the demands for data and associated data acquisition processes are diverse. Since the infancy of GIS, efforts in data acquisition and digitization have accounted for 80% or more of a project's resources on average (Goodchild, 2003). As a result, a variety of value-added data service providers emerged. Third, inequality in data access widely exists due to technical issues and policy on information access. The landscape of the geospatial world can be characterized by a wide spectrum of "haves" and "have-nots" (Lee and Shumakov, 2003). A multitude of data sources from multi-scale vector spatial databases to the sub-meter raster satellite images and LIDAR data are readily available in the U.S. On the other hand, many poor nations lack of even the basic digital data infrastructure. Finally, increasingly complicated applications require the use of data from different formats, different scales, different resolutions, and different times.

If DGIS serves as one of the lifelines of society in this information age and user interface and system interoperability functions serve as the blood vessels, then data/information would be the blood of this lifeline. Thus, data integration is a vital component of DGIS. Data heterogeneity over time not just impedes data integration, but over time, it compounds problems of data integration. From the computing perspective, two approaches may be considered for data integration. One way is to convert all types of data into a common type. This is not only a formidable process, but also error-prone since changes maybe applied to the original data by the third party. Another approach is to develop data "wrappers" to match different types of data to a common format when data are retrieved from databases and transmitted to another user.

Data integration is also closely related to data update management. DGIS can improve the efficiency of data sharing and distribution. Yet, data update maintenance remains to be a challenging issue as the development of DGIS moves forward. It has become increasingly important since data dissemination is often demanded in virtually real time. Traditionally, DGIS uses data cascades down from the top of the societal hierarchy, such as from the federal government agencies and large research institutions, to local users. However, more applications need to integrate real time on-site observation data from GPS, remote sensing, and ground surveys into existing databases. There is no effective mechanism in place to integrate data upward along the hierarchy and facilitate the subsequent data management from bottom up. Local users and data providers need to have the capability to update, upload, and manage the uploaded data and information. Interactive update maintenance requires consistency, which can be achieved through passive and active consistency strategies. A passive strategy can be used for those data with low frequency of access. Then data consistency check is performed only when the data are needed. An active strategy is executed through pre-scheduled periodic consistency checks or through an interruption-trigger mechanism (change prompts an update check). Further, data could also be attached with a creation or an expiration time tag for consistency check, in case of multiple data uploads from different users in the same area for the same purpose.

Spatial data mining: information is the key for successfully building a third stage DGIS application. Accurate and timely information are needed to be mined from large amount of data. Just within NASA DAACs, petabytes of geospatial data have been collected and archived (http://nasadaacs.eos.nasa.gov/about.html) through different satellite sensors and other acquisition methods, and the volume of geospatial data is increasing at a rate of terabytes per day. Since there are huge volumes of datasets that are archived and ready for use, it is essential to retrieve and extract accurate and relevant information from the archived datasets or real time data in a timely fashion (Miller and Han, 2001). The attributes of geographical features can be mined using generic data mining methods (Han and Kamber, 2000). However, special data mining techniques are needed to discover location characteristics, spatial relations and other spatial characteristics (Kriegel, 2004; Shekhar et al., 2002). Some scholars, such as Lu and Han (1992), had begun to apply data mining techniques on geospatial data to discover information and knowledge since the early 1990s.

Spatial data mining research focuses on discovering interesting and previously unknown, but potentially useful patterns from large geospatial databases (Shekhar et al., 2002). Research activities include: 1) definition of database primitives for spatial data mining (Ester, 2000); 2) algorithms for location prediction (such as Ester 1998; Shekhar et al., 2002), spatial outlier detection (Shekhar et al., 2003), co-location pattern discovery, and constraint-based clustering (Ribarsky et al., 1999); 3) adoption of spatial data mining techniques in various applications, such as transportation (Miller, 1999) and information extraction from different types of data including images (Lillesand and Kiefer, 2000).

Miller and Han (2001) pointed out that the future research direction of spatial data mining lies in the areas of geographic data warehouse, spatio-temporal representation, geographic data types, user interface, new applications, and integration with GIS and spatial analysis. Within the DGIS environment, spatial data mining will have its special opportunities and challenges: 1) the networked data resources and data processing components provide cross-dataset spatial data mining opportunities. For example, the process may integrate mining results from both satellite imageries and socio-economic data across computer networks; 2) applications of spatial data mining in the real world become feasible for large scale projects, such as that in nature hazard applications; 3) performance will become a challenging issue when a large volume of data are fed into the mining process and timing becomes critical; 4) a data model and relevant structures that can take advantage of DGIS architecture are needed to organize data to facilitate the discovery of information and knowledge within a distributed network environment; and 5) the development of algorithms to handle the heterogeneous problems discussed early when data mining is performed on the dispersed datasets accessible through the DGIS infrastructure .

Data and system security: The flow of geospatial data and information in the virtual world directly affects the functions and operations in the real world. Widespread implementations of high-performance distributed computing hinges critically on the availability of appropriate security mechanisms (Foster et al., 1998). Security is crucial to the development of DGIS. The heterogeneous nature of data resources and their security policies make security schemes complicated in any distributed or Grid computing environment (Joseph and Fellenstein, 2004). The security issues in DGIS encompass a couple of important fronts: network system security and data access and distribution security. Because the distributed computing environment of DGIS comprises a large number of computers and complicated computing processes over large geographic areas, the security challenges are complicated. A daily life non-computing example below is used here as an analogy to illustrate the complexity of the issues.

Most people, if not everyone, would understand the importance and security complexity of transporting top-secret information or critically important goods across a train line. First, the infrastructure has to be secured and operational. The communication codes have to be set up to avoid the risk of possible collisions and to ensure smooth passage without unnecessary delays across different stations in different administrative areas. Second, all the passengers and crews have to be registered and even background checked for security clearance. Third, the top-security information or goods have to be specially packed to provide additional layers of security. Finally, an emergency response protocol has to be in place, in case of a security breach or disastrous accident. In a similar vein, the challenging issues in DGIS data and system security can be summarized in the following areas:

- Multi-tier security policy to secure distributed channels: The virtual world runs on the information highways or broadband wireless airways and security starts with a secured and reliable infrastructure. There should be global and local security policies and inter-domain access trust. The distributed or Grid security policies must focus on inter-domain interactions and the mapping connection between inter-domain operations and local security policies (Foster et al., 1998a).
- Communication security mechanism: once the secured channels are in place, the next layer of security is about communication through the channels. Parallel authentications of both users and resources are required to ensure the integrity and confidentiality of communication (Foster et al., 1998b).
- Data security: The third layer of security is about the data resource itself. Many DGIS may deal with national defense data or sensitive environmental projects such as nuclear waste disposals. It is not only important to ensure the safety of the computing infrastructure (hardware & software) and communication integrity (rightful users and authentic resources), but equally important is to guarantee the integrity of the data resources themselves. Existing security strategies are not directly applicable to meet the needs for detecting changes, describing changes,

and identifying the time of changes. Securing geographic data also differs from encrypting messages.

- Security mapping: despite the three-layer security strategies mentioned above, potential security breach is still possible. It is critical to monitor and track where a breach takes place and what type of impacts it may have. More importantly, it is not adequate to track the virtual world IP address or domain of the breach. It is more crucial to link the virtual world to the real world because the law enforcement agencies can only operate with geographic addresses and districts. Security mapping is to map out the interconnections between the two the two types of addresses.

In short, network security has reached a new level of challenge in light of the rapid development of high speed computing and wireless communication. Wireless networks present a security nightmare to computer users (Scholz, 2002). The security breach and damages related to the use and distribution of geospatial data are hard to monitor and far reaching. By and large, there should be a security mechanism to monitor who is accessing the data, when and why the data are accessed, and what the data are used for. The 9/11 tragedy could be interpreted both as an example of a security failure in sharing data by national security agencies, and a lesson of geospatial data being accessed and used by the wrong people. A secure DGIS will be crucial in the applications of homeland security, geospatial intelligence and other sensitive environments. A successful security solution has to take DGIS into consideration.

4. Conclusion

DGIS is a rapidly evolving technology. On one hand, new applications of DGIS are constantly launched to provide GIS services in a distributed environment. These new applications are exemplified by the three evolution stages of DGIS development. On the other hand, innovative applications present mounting challenges when DGIS advances to its later (third) stage of development.

The evolution of DGIS is reflected in many aspects, such as the types of applications; the user accessibility to GIS, other technologies used in DGIS in terms of hardware and software, and the professional expertise of developers in advancing DGIS. Geographically, DGIS applications are expanding globally as far as the network, wired or wireless, can reach. The diverse DGIS applications, dispersed DGIS communities, and disparities in accessing and using DGIS have resulted in the three-stage scenarios of DGIS evolution. Currently, the third stage is the focus of research and development efforts.

Meanwhile, rapid development of DGIS is accompanied by some daunting challenges. We reviewed the important computing challenges including issues related to 1) efficiency of data access and dissemination in streamlined user-interfaces, 2) interoperability impeded by heterogeneous hardware, software, and data environments, 3) data integration and update to maintain data integrity, 4) spatial data mining in finding feasible and optimal ways for deriving and discovering geographic information effectively and efficiently; and 5) the important security aspect to ensure that the system operates securely as designed.

The research and solutions developed for these computing challenges will provide a computing infrastructure to support DGIS possessing characteristics of a third stage system. The challenges also include non-computing aspects, such as management and application-specific modeling.

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