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Integrating Web-based GIS and image processing tools for environmental monitoring and natural resource management

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Abstract. The combined powers of Web-based geographic information systems (GIS) and on-line remote sensing tools can significantly reduce the high cost and labor associated with environmental monitoring and natural resource management. This paper introduces an integrated Web-based GIS architecture by combining three levels of geographic information services (GIServices): data archive, information display, and spatial analysis. A prototype Web site, WGAT (Web-based GIS and Analytic Tools), has been developed to provide easy access of geospatial information and to facilitate Web-based image analysis and change detection capabilities for natural resource managers and regional park rangers. The Web-based integration framework emphasizes user-oriented services, distributed network environments, metadata standards, communication protocols, client/server computation, and ubiquitous access.

Key words: Web-based GIS, remote sensing, GIServices, environmental monitoring

1 Introduction

The advent of the Internet and Web-based geographic information systems (GIS) technologies provides a convenient and efficient way to access and disseminate geospatial data and remotely sensed imagery. There is a great

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potential for using Web-based GIS and on-line image analysis tools in the areas of natural habitat preservation and environmental monitoring. The combined powers of data collection through remote sensing techniques and geospatial analysis tools by means of the Internet can significantly reduce the high cost and labor associated with traditional field monitoring and environmental resource management methods.

However, current development of Web-based GIS mainly focuses on vector-based geospatial data rather than raster-based remotely sensed imagery. This paper argues the importance of integrating raster-based image data and vector-based feature data under a single Web-based framework from a software developer's perspective. An integrated Web-based GIS architecture was introduced by combining three levels of Web-based geographic information services (GIServices): data archive and search, information display and query, and spatial analysis functionality. A prototype system, WGAT (Web-based GIS and Analytic Tools, http://map.sdsu.edu/arc) has been developed to provide easy access of geospatial information and to facilitate the adoption of image analysis and change detection methods for natural habitat management and monitoring. A three-level Web service framework was created to monitor multi-species habitat and land cover changes for the Mission Trail Regional Park (MTRP) located in San Diego, California. Figure 1 illustrates the three levels of services and the actual implementation of the prototype Web site.

The first level of integration is the data archive/search service. A Web-based data warehouse was developed for archiving, accessing and downloading both GIS databases and remotely sensed imagery. The major integration requirement is the adoption of a standardized metadata format for both GIS layers and remotely sensed imagery. The Web-based data warehouse can help users to index and search the contents of metadata.

The second level is the information display and query service. Multiple interactive map servers and image servers were established to provide Web-based mapping functions for the display of land use, vegetation, soil, trails, roads, and remotely sensed satellite images. The major integration require-

Level of integration	Implementation and requirements
Level three: *Spatial analysis*	***On-line spatial analytical tool*** • Ubiquitous access • Client/server computation balance.
⇧	
Level two: *Information display and query*	***Internet map/Image server*** • Web-based display • Communication protocol
⇧	
Level one: *Data archive and search*	***Web-based data warehouse*** • Standardized metadata • Metadata index/search

Fig. 1. The three-level integration of Web-based GIS and on-line remote sensing tools

ment at this level is providing an effective Web-based display mechanism and a client/server communication protocol

The third level is the spatial analysis service. Several Java-based on-line analytical tools (Java applets) were developed to provide advanced image comparison capabilities and functions for land cover change detection analysis. The implementation of Java applets can provide ubiquitous access for natural resource managers and park rangers. The design of Java runtime environments can create a balanced client/server computation framework.

There is an interdependent relationship between each service level. From a system implementation perspective, the lower level services are the prerequisite of higher level services. For example, to create a Web-based map display and query (level two), the Web server has to connect to a completed GIS database with standardized metadata (level one). The functions of metadata index/search in level one will also be used in level three (spatial analysis) for advanced GIS functions and geocomputations. From a user's perspective, the higher level services are the extended transform of the lower level services. GIS users can download geospatial datasets from data warehouse (level one), and then use their own GIS software to perform map display (level two) or advanced spatial analysis functions (level three) using their desktop GIS packages.

Under the Web-based framework, all three-levels of service were accessible by using a standard Internet Web browser, which serves as the image viewer and interface to a suite of image processing and GIS tools. The standard Internet Web browsers and easy-to-use interfaces provide a flexible means to access both spatial information and powerful geospatial analytical tools for environmental monitoring tasks. The project research team worked closely with the park rangers from the Mission Trail Regional Park in San Diego, CA to develop and test the prototype analytical tools and demonstration applications of this Web-based system. Park rangers and several GIS professionals evaluated the prototype system, graciously provided their expert review, and responded to the project team's user-needs questions. The project data sets include fifteen GIS layers from the San Diego Association of Governments (SANDAG) and two types of remotely sensed imagery: Airborne Data Acquisition and Registration (ADAR) system and IKONOS. The ADAR 5500 system is an airborne multispectral digital camera system with one meter spatial resolution. The IKONOS satellite is a high-resolution commercial satellite system with one meter spatial resolution in panchromatic imagery mode and four meters spatial resolution in multipectral infrared imagery mode.

The key concept in the design of this prototype is to integrate Web-based GIS and on-line remote sensing tools under a single framework. The following section illustrates the challenges of combining these two types of services and introduces related Web technologies and software.

2 Web-based GIS versus on-line remote sensing tools

The integration of GIS and remote sensing has been an important topic in both GIS and remote sensing communities for a long time. Ehlers et al. (1989) introduced a three level integration process between GIS and remote sensing. The first level included simultaneous display of both vector and raster data. The second level required dynamic data exchanges and display functions via the same user interface. The third level of integration was called total integration, which included both fundamental data model integration and software development. Estes and Star (1993) introduced a concept of integrated GIS (IGIS) that processed remotely sensed imagery as well as raster and vector data sets in a consistent fashion. Fonseca et al. (2002) added a fourth level of integration to Ehlers's three-level framework. The fourth level is the knowledge integration for GIS and remote sensing applications. By using ontologies and a knowledge-based system, an ontology-driven system can provide semantic integration of aerial images and GIS and allow more flexible extraction of geospatial information (Fonseca et al. 2002). These previous studies clearly indicate the essential need to integrate GIS and remote sensing applications. Portions of this paper and the proposed Web-based framework are inspired by these studies. However, the three-level Web-based integration framework proposed in this research is different from the system-based integration mentioned in Ehlers's article. The Web-based integration framework for GIS and remote sensing tools developed in this project needed to consider the nature of the distributed network environments, metadata, client/server architecture, cross-platform programming tools, and software interoperability. Also, the three-level integration framework emphasizes user-oriented services rather than functionality-oriented systems.

The history of Web-based GIS can be traced back to the development of the Xerox Map Viewer in 1994 (Putz 1994). The Xerox Map Viewer used a Web Browser via HyperText Markup Language (HTML) format and Common Gateway Interface (CGI) programs to provide interactive mapping functions via the Internet. The technical framework of the Map Viewer was followed by many early on-line GIServices applications. Another important research project was the Alexandria Digital Library Project (Buttenfield and Goodchild 1996; Frew et al. 1998), which explored comprehensive services for on-line spatial queries, map browsing, and metadata indexing. Distributed component technologies and data/interface standards are also the foci of the Internet mapping research, including OpenGIS specification (Buehler and McKee 1998), ISO/TC211 Standards (Ostensen 1995), component-oriented GIS (Li and Zhang 1997), and virtual data sets (Vckovski1998). Besides the development of academic research, the GIS industry is also developing several software packages to provide on-line mapping functions, such as ESRI's ArcIMS (Internet Map Server), INTERGRAPH's GeoMedia Web Map, AutoDesk's MapGuide, and GE SmallWorld's Internet Application Server.

In contrast, the early development of on-line remote sensing tools mainly focused on data dissemination and catalog search functions. One of the best examples is the Earth Observing System Data and Information System (EOSDIS) developed by National Aeronautics and Space Administration (NASA) during the early 1990s. EOSDIS Version 0 (V0) system was developed as an early prototype to provide an interoperable inventory layer over existing, independent data systems. The main goal of EOSDIS was to support the search and order access to heritage data collections held by NASA's Distributed Active Archive Centers (DAACs) (NASA, 2002). EOSDIS has been operating since August 1994 at eight Distributed Active Archive Centers around the United States and interoperating with six foreign sites. The early design of EOSDIS utilized the basic Internet networking techniques, such as remote X-window display, UNIX operating systems, and TCP/IP communication mechanisms. After the advent of the World Wide Web (the Web), the development of EOSDIS shifted to Web-based technologies and the Earth Observing System (EOS) Data Gateway (EDG) was created to provide multiple search functions for remote sensing data available in EOSDIS. The current design of EOS Data Gateway provides a Web-based access point for end-users to search, query, and order remote sensing data. One unique feature of EOSDIS is the introduction of an open architectural concept and the design of an interoperability infrastructure between clients and data providers (Elkington et al. 1994).

Different from Web-based GIS and Web-based mapping tools, most on-line remote sensing applications mainly focus on cataloging functions and graphic display. Very few applications provide advanced functions for image analysis, such as the display of multiple spectral bands, georeferencing, image overlay, change detection, etc. Starting in the early 2000s, along with the progress of Web technologies, including Java programming and image compression techniques, the remote sensing industry began to develop on-line remote sensing image servers and viewers, such as ER Mapper's Image Web Server (IWS) (with ECW viewer), Liztech's Content Server (with MrSID image format), and PCI's Geomatica WebServer. However, these software packages still lacked fully integrated capabilities with other GIS Internet Mapping packages. The single exception is the recent development of ER Mapper's IWS plug-ins with ESRI ArcIMS image server.

A major challenge to the full integration of the Internet map server with the remote sensing image server is the heterogeneous architectures between them. The different functionality required on the client side components (viewers) is another major hurdle. Client/server problems are caused by the three fundamental differences between Web-based GIS and on-line remote sensing database sources: *data archive formats*, *geographic information display*, *and spatial analysis functions*. To conquer these fundamental problems, this paper suggests a fully integrated framework by combining the three levels of services. The following sections illustrate the detailed specifications of the three level integrations between Web-based GIS and on-line remote sensing database sources. These services have been tested for environmental monitoring and natural resource management tasks to demonstrate their potential capabilities.

3 Level one: Data archive and search services

3.1 The development of data warehouse and metadata standards

The first level of integration between Web-based GIS and on-line remote sensing database sources is the data archive and search services. The Alexandria Digital Library and NASA EOSDIS Data Gateway, as described earlier, are good examples of data archive and search services. The Internet and the Web become the storage devices or media to archive and deliver GIS data layers and remotely sensed imagery. The Web also provides excellent user interfaces to catalog, index, and search these data sets in the form of digital libraries. Two major forms of data archive and search services are *data warehouses* and *data clearinghouses*. The role of data warehouses (or data archive centers) is to archive data and to provide data access, download, and preview mechanisms. Data clearinghouses are built upon distributed metadata databases via multiple data warehouses or other data clearinghouses (Tsou 2002). Current development of data clearinghouses utilizes the Z39.50 protocol to index and access multiple metadata repositories remotely. At present, Federal Geographic Data Committee's (FGDC) National Spatial Data Infrastructure (NSDI) and associated data clearinghouse nodes adopt this approach to provide metadata search and query functions.

To create a successful data archive and search service, metadata is the key issue for a full integration of both GIS layers and remotely sensed imagery. Metadata can bridge the heterogeneous environments in GIS databases and remote sensing data sets. However, the major challenge is to design a comprehensive metadata standard for both GIS data layers and remote sensing data. Currently, ISO 19115 Metadata Standard is the major international metadata standard (previously published as ISO15046-15) created by the International Organization for Standardisation (ISO) Technical Committee (TC) 211. The ISO metadata standards proposed a conceptual framework and an implementation approach for geospatial metadata that were developed partially based on the 1994 FGDC's Content Standard for Digital Geospatial Metadata (CSDGM) (FGDC 1998; ISO/TC 211/WG3, 1998). The major advantage of ISO 19115 and CSDGM Metadata Standard is its flexibility in creating extensions and profiles for various applications. With the ISO 19115 and CSDGM Metadata Standard, the remote sensing community can define the metadata extensions for remote sensing research and applications. In 2002, the extension for remote sensing metadata was created and documented in the Content Standard for Digital Geospatial Metadata: Extensions for Remote Sensing Metadata, FGDC-STD-012-2002 (FGDC 2002). The following section introduces the actual implementation of a data warehouse prototype combining both GIS layers and remotely sensed imagery for environmental monitoring and management tasks.

3.2 The data warehouse implementation

The project data warehouse was populated using selected GIS datasets from the San Diego Association of Governments (SANDAG) archive and two types (airborne and satellite) of remotely sensed imagery. Two series of metadata are associated with the downloadable GIS layers and images (Fig. 2). The first series of metadata was for remotely sensed images which included 1998 (June 27, 1998), 1999 (May 26,1999), 2000 (May 3, 2000) ADAR imagery, 1995 (June 23, 1995), 1997 (May 4, 1997) Digital Orthophoto Quarter Quadrangle (DOQQ) imagery, and 2000 (June 29, 2000), 2001 (May 30, 2001) IKONOS multispectral imagery. The second metadata series described the GIS themes which included 15 different map layers, such as roads, trails, land use, soil types, vegetation, etc.

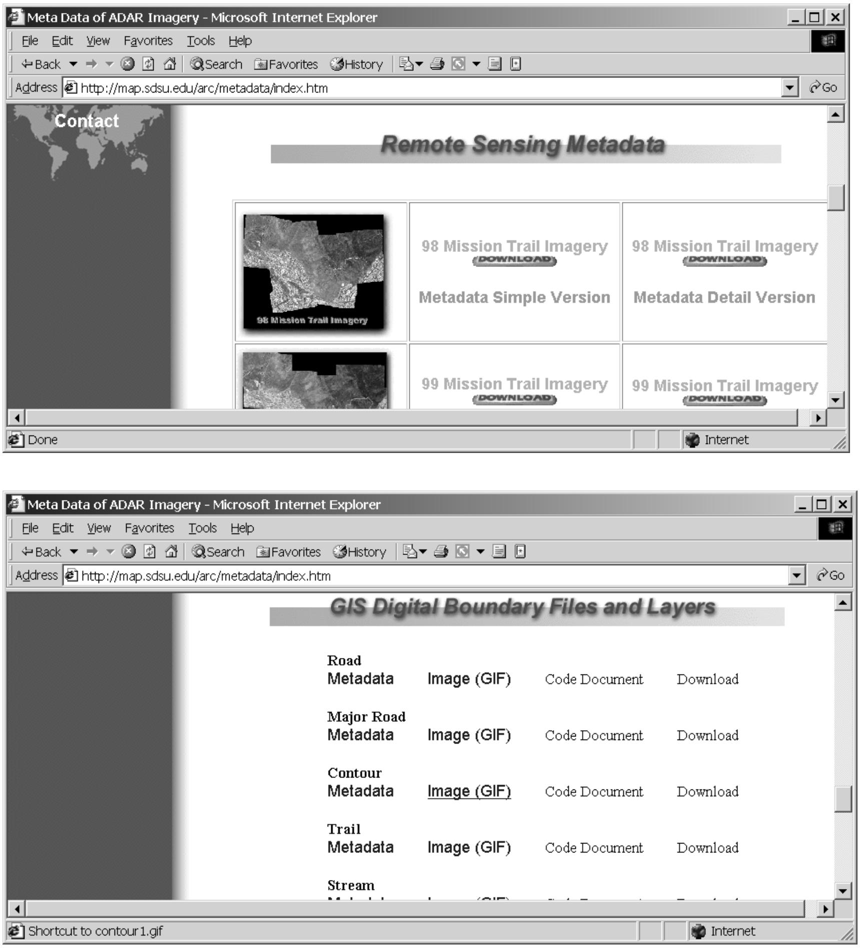

Fig. 2. The data warehouse implementation

Four major functions were provided by the data warehouse prototype: *metadata display*, *data preview*, *data download*, *and metadata search/ index*. The metadata of each GIS layer and remotely sensed image were displayed in HTML format on the data warehouse pages. Each metadata file also included a thumbnail image for preview of the actual data sets. The design of the data warehouse also included a data download button to allow users to download GIS layer exchange files and compressed remote sensed images from the Web server. Another major function of the data warehouse was to search the contents of metadata. The metadata search mechanism was created to allow users to type keywords for searching and querying the metadata. The search engine was implemented using Microsoft IIS Index Services, a built-in function on a Window 2000 server. The search engine indexed all metadata records stored in HTML format allowing efficient metadata search and query functions.

In general, the implementation of data warehouse provides an easy-to-use mechanism for resource managers and park rangers to access or download GIS data and remotely sensed images that can be readily combined or integrated with their own local GIS software projects. The data warehouse prototype introduced here adopted an easy and direct approach for both metadata contents and search mechanisms by utilizing existing software and services (HTML documents and IIS index engines). On the other hand, there are several potential limitations in the current design of data warehouse. For example, the search mechanism only adopted text-based keyword matching rather than semantic query and spatial-oriented operations. In the future, the development of data warehouse, data clearinghouse, and metadata search mechanisms will need to include more advanced methods for the full integration of Web-based GIS and on-line remote sensing sources. The adoption of new metadata extensions for remotely sensed data (FGDC 2002), eXtensible Markup Language (XML)-based information mediation for metadata search and indexing tasks (Gupta et al. 1999), object-oriented frameworks (Kemp 1999) and operational metadata schemes (Tsou 2002) may establish more comprehensive and effective frameworks for data archive and search services.

4 Level two: Information display and query services

4.1 Web-based display and communication protocols

The second level of integration between Web-based GIS and on-line remote sensing sources is the information display and query services. Many commercial software packages offer information display services by installing their specialized map servers. However, the major challenges for the integration of Web-based GIS and remote sensing tools are the compatibility of *data transmission/display* format and client/server *communication protocols*.

Traditionally, the display of GIS data mainly adopts the vector-based data model as opposed to the raster-based model for remotely sensed imagery. The same problem happens on the Web-based environments, especially in the design of client-side viewers and server-side map engines. The early development of Web-based GIS adopted the raster-based images for map display. For example, the Xerox map server converted vector-based layers into a GIF image (raster-based) on the server side and then sent the GIF image to the client side in HTML format. The users viewed the actual map as hyperlinked pictures on their Web browsers. More recent development of Web-based GIS services began to adopt the vector-based display format, such as Vector Markup Language (VML), Scalable Vector Graphics (SVG), and Geography Markup Language (GML) (Zaslavsky 2000; OGC 2003). Vector-based display on the client-side viewers can provide more comprehensive display functions than raster-based pictures, such as rapid zoom-in/out, customizable map symbols, and layer stacking order. The drawback of vector-based display is the incompatibility with raster-based remote sensing data. Therefore, the major challenge for information display services is to utilize both vector-based and raster-based display on a single Web browser or viewer. One possible solution is to redesign the client-side viewer so that it can access both vector-based map servers and raster-based image servers at the same time. However, such a function may require a "thick-client" solution, where the size of viewer software modules will be larger than regular Web plug-ins or applets. It will be difficult for users to download such large software modules via current available network bandwidths.

Another challenge for information display and query services is the design of the communication protocol between Web clients and servers. To provide an interactive, dynamic map display, client-side viewers need to send user's request (such as zoom-in, zoom-out, add, query) back to the servers. The servers will then generate new maps or information and send them back to the client-side viewers. The design of client/server communication protocol must make sure all the client requests can be understood by the servers and vise versa. Currently, most GIS vendors have their own proprietary communication protocols for Internet map servers and image servers. For example, ESRI's ArcIMS utilizes ArcXML for its client/server communication protocols. ER Mapper's Image Web Server uses ECW Protocol (ECWP) for accessing ECW compressed images and Web image servers. These vendor-based, specialized protocols may cause serious problems for client/server communications across different Web-based applications and services. To resolve this problem, the Open GIS Consortium (OGC) initiated two types of communication protocol standards for Web-based GIS. The first is the OpenGIS Web Map Server (WMS) Implementation Interface Specifications, which provides guidelines for current image-based Internet map servers with the specifications of HTTP contents and Uniform Resource Locators (URLs) communication syntax (OGC 2002a). The second standard is the OpenGIS Web Feature Server (WFS) Implementation Specification. The Web Feature Service allows a client to retrieve geospatial data encoded in Geography Markup Language (GML) (vector-based) from multiple Web Feature Services (OGC 2002b). The WFS adopted XML-based communication interfaces and GML for describing vector-based features (points, lines, and polygons). Although the development of WMS and WFS may solve the potential problem in vendor-based communication protocols, one issue remains unresolved: how image-based WMS and vector-based WFS can be integrated. The differences between WMS and WFS reflect the fundamental challenge of information display, which is the incompatibility between a vector-based map and a raster-based image.

One possible development of client/server communication protocols is to adopt the Web services frameworks. Currently, Web services comprise the most exciting developments within Web-based GIS and on-line remote sensing sources. Web services are formed by the integration of several key protocols and standards: XML, WSDL (Web Services Definition Language), SOAP (Simple Object Access Protocol), and UDDI (Universal Description, Discovery, and Integration). The power of Web services is their combination of these elements under a single user-friendly operating environment using a Web-based user interface (Tsou and Buttenfield 2002).

The next section illustrates a interim solution for the integration of both Web-based GIS display and remotely sensed data. The Internet map server implementation goal was to adopt a raster-based Internet map server (ArcIMS Image server) and JavaScript-based dynamic HTML documents (DHTML) to display both GIS layers and remote sensing images. Although this approach is not an optimal solution, it did fulfill the function of information display and query services from the users' perspective.

4.2 The implementation of internet map servers

The prototype Web site demonstrated in this project used ESRI's ArcIMS to provide interactive Web mapping services. ArcIMS supports OpenGIS WMS Implementation Interface Specifications 1.0 (ESRI, 2001). The Internet Map Server provides comprehensive on-line mapping capabilities, including *zoom-in*, *zoom-out*, *pan*, *spatial query*, *buffering*, and *measuring*. Two types of Web mapping services (HTML viewer and Java Viewer) were created for different clusters of GIS tasks. This project also utilizes JavaScript functions to create a dynamic map display function where users can move the mouse cursor to overlay different GIS layers on a remotely sensed image (Fig. 3).

One of the unique features in the prototype is the integration of the GPS data, remotely sensed imagery, and GIS layers using a single Internet Map Server. This project gathered several GPS data layers, such as park trails and

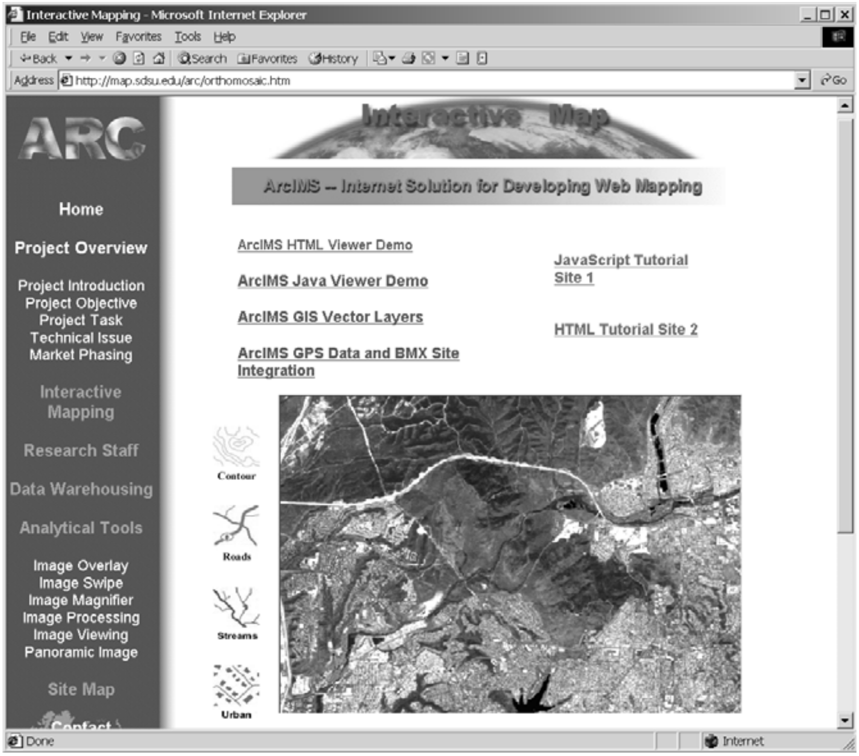

Fig. 3. The JavaScript-based dynamic Web mapping

land cover change sites generated by MTRP park rangers with their hand-held GPS devices. The GPS data sets were transformed into GIS data format (shapefiles). These data sets were overlaid with georeferenced ADAR images (Fig. 4). Park rangers and habitat managers used these Web-based mapping services to perform various tasks, such as monitoring the change of landform, querying the locations of sensitive plants, and evaluating the accessibility of park facilities.

By implementing dynamic Web mapping services, natural resource managers and park rangers can access geographic information and remotely sensed data using a typical desktop computer without installing expensive GIS and remote sensing software packages. Moreover, the Web-based mapping services become a wonderful education tool for the public learn about the importance of environmental conservation and habitat management. The next section focuses on the third level of integration: spatial analysis services and their related technologies.

5 Level three: spatial analysis services

5.1 The development of on-line spatial analytical tools

The third level of integration between Web-based GIS and on-line remote sensing facilities is spatial analysis services, which is the most advanced part of the integration process. The scope of on-line spatial analysis services includes Web-based GIS functions (address matching, network analysis, reselection, etc.) and advanced remotely sensed image analysis (change

Fig. 4. The integration of GPS data, remotely sensed imagery, and GIS layers

detection, image classification, multiple-bands display, etc.). Different from the information display and query services, spatial analysis services provides users the ability to create new information or data by using Web-based spatial analysis tools or GIS components. There are two major challenges in this level: *ubiquitous access* and *client/server computation balance*.

The first challenge is to provide ubiquitous access to spatial analysis functions across heterogeneous operating systems and Web browser environments. Traditional GIS programs and analytical functions are machine-dependable and vendor-based. To create Web-based GIS modules or analytical functions, software developers must choose a universal, interoperable programming environment for implementation. Currently, several programming languages and techniques, such as Java, ActiveX controls, and C# (C-sharp), support platform-independent applications across the Internet (Orfali and Harkey 1997). There is great potential in utilizing these techniques to create comprehensive Web-based GIS and image analysis tools. However, some technical issues remain to be resolved for the full integration of Web-based GIS and remote sensing tools. For example, the required Application Programming Interfaces (API) and shared programming libraries for Web-based GIS might be quite different from remote sensing applications. Web-based GIS typically focus on the vector-based computations and the database linkage between spatial features and attribute records. Remote sensing applications generally require advanced 2D graphics and image functions. To communicate between Web-based GIS modules and remote sensing applications, standardized API or object component brokers need to be defined for both software components. Many software companies and GIS vendors are focusing on this issue, hoping to come up with a better solution in the near future.

The second challenge is to create a balanced computation load between client machines and server machines. Since most GIS analysis and remote sensing image processes require a great amount of computing power, it is highly desirable to assign the major computation tasks to the most powerful of the available machines. There are two possible approaches, a server-side solution or a client-side solution. The server-side solution uses the server to perform the major computation tasks. The role of clients (as thin clients) is that of a terminal for sending out users' requests and receiving final results. Currently, Web-based Common Gateway Interface (CGI), Java Servlets, Active Server Page (ASP), and Web Services adopted this type of server-side solution. The client-side solution puts the major computation tasks on the client side machine (as thick-clients). The GIS functions or remote sensing applications are dynamically downloaded into the client side Web browser or desktop. The role of the server becomes that of a software archive center for the end users. All major computation and spatial analysis functions happen on the client side machine. Java applets and ActiveX controls are two popular types of client-side solutions.

To integrate Web-based GIS components and remote sensing applications, software developers must consider the nature of their functions and computation needs. One possible solution is to create a dynamic, LEGO-like environment for spatial analysis services. The LEGO metaphor refers to the well-known children's toy blocks that can be interlocked and stacked. The LEGO architecture may persist only briefly, for the completion of a single GIS or remote sensing task. Then the LEGO modules disperse, to be rearranged and restacked in a different configuration for a different task (Tsou and Buttenfield 2002). The following section introduces an actual implementation of Java-based, on-line image analysis tools for the integration of Web-based GIS functions and remote sensing applications.

5.2 Implementation of Java-based tools

This project adopted the Java programming for the implementation of on-line GIS and remote sensing analytical functions. One primary consideration in choosing a development platform is that the language should provide database connectivity and comprehensive image processing and display functions. Java is a pure object-oriented language, designed to enable the development of secure, high performance, and highly robust applications on multiple platforms in heterogeneous, distributed networks (Gosling and McGilton 1996).

Current Java System Development Toolkits (JDK) provides a series of well-defined APIs for image processing and display, such as Java 2D API and Java Advanced Imaging (JAI). The Java 2D API is a set of classes for advanced 2D graphics and imaging, encompassing line art, text, and images in a single comprehensive model. The Java Advanced Imaging APIs are used for manipulating and displaying images. They range in complexity from simple operations, such as contrast enhancement, cropping, and scaling, to more complex operations such as advanced geometric warping and frequency domain processing. These APIs are used in a variety of applications, including geospatial data processing and medical imaging. This project utilized two APIs (2D and JAI) to customize Web-based user interface and analytical tools.

There are two procedures for the implementation of Java applets, a compile-time environment (server-side) and a run-time environment (client-side). The compile-time environment can be constructed by using the Java Development Kit (JDK), which include a Java compiler (Javac.exe), a Java interpreter (Java.exe), a Java debugger (jdb.exe), and several standardized Java libraries (Krammer 1996). Programmers can use the Java compiler to generate a Java class from a text-based Java source code to a Java byte-codes format and put the class on the server-side machine. Then, the Java class is ready for on demand download by users from client machines.

This project adopts Java applets to provide on-line analytical functions for remotely sensed image analysis and change detection. The principle reason for selecting Java applets is that Java applets are specifically designed for the distributed network environment, such as the Internet and Intranet. They are capable of providing advanced image processing and comparison functions suitable for habitat monitoring. One of the unique capabilities of the graphic user interface (GUI) toolbox design is that it enables users to open multiple Java windows at the same time (Fig. 5). The ability to open multiple windows simultaneously gives analysts much greater flexibility in conducting image comparison and spatial analyses.

There are eight independent Java applets available in the toolbox, which were originally developed under this project. Examples of representative

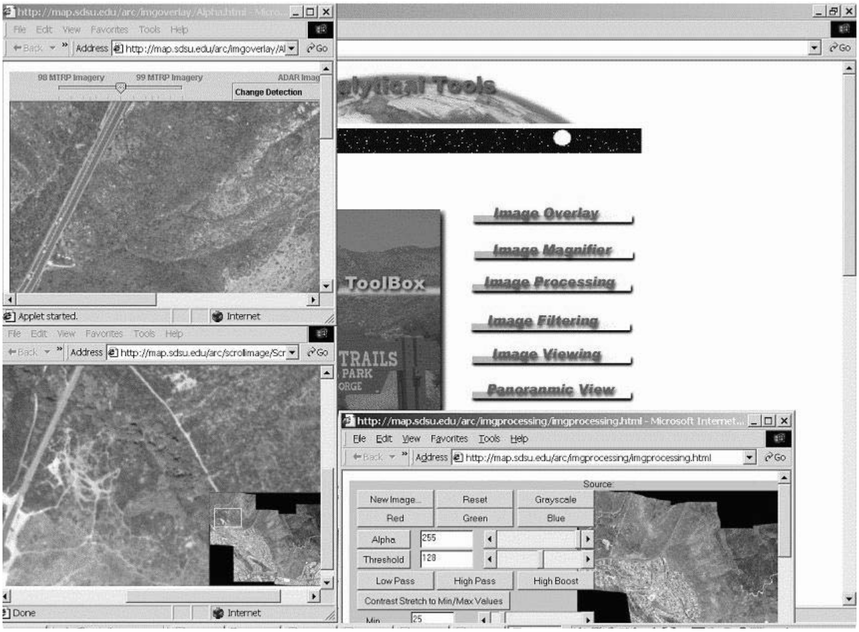

Fig. 5. Multiple Java applets opened from the Image Analysis Toolbox

Java applet source code are listed below. (A detailed description of these Java source codes can be accessed from the project's Web site http://map.sdsu.edu/arc).

```
class CompPanel extends JPanel {
  Image theImage;
  Image theImage2;
  public CompPanel(Image theImage, Image theImage2) {
    this.theImage = theImage;
    this.theImage2 = theImage2;
  }
  public float changeRule(float a) {
    alpha = a;
    swipeWidth = (int)(a * getSize().width);
    System.out.println("a = " + a);
    repaint();
    return a;
  }
```

In this Java example, the analysis function is to overlay two remotely sensed images (theImage and theImage2) and then switch the two images' order of display for the purpose of detecting changes (usually temporally) between the two images. The display of images is created by the [CompPanel] object (Comparison Panel) which has one image analysis function (changeRule).

Eight different Java applets were implemented in the Image Analysis Toolbox, including Image Overlay-I, Image Overlay-II, Image Swipe, Image Magnifier, Image Comparison, Image Processing, Image Filtering, and Image Viewing. The following paragraphs describe four representative Java applets and their analytical functions for remote sensing and change detection analyses.

5.2.1 Image Overlay I and II

Image Overlay-I applet can overlay two remote sensing images and allow a pixel-by-pixel comparative display of the two image files by means of a slider bar. This applet enables visual comparison of image changes for monitoring land covers and habitats. For example, users can compare the 1998 ADAR imagery with the 1999 ADAR imagery to view land cover changes resulting from a fire in Mission Trail Regional Park (Fig. 6).

The next Java applet is called "Image Overlay-II," and is an improved version of Image Overlay-I. The research team improved the function of Image Overlay based on the suggestions from user feedback and questionnaires during the prototyping. Image Overlay-II integrates with zoom-and-scale functions and allows analysts to explore multi-temporal images using an interactive blend/fade control for improved interpretation of change detection. Users can move the slider back and forth, and swap top and bottom images. In addition, the zoom-box can be dragged, enlarged or reduced to display specific image details. This improved Java applet can perform more flexible image overlay functions by zooming to a small area on the image (Fig. 7).

5.2.2 Image Processing

Two Java applets were developed for the purpose of image processing (Fig. 8). The first Java applet provides basic image processing functions

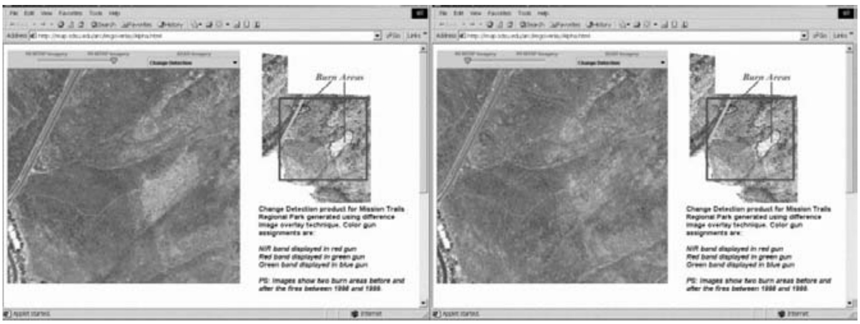

Fig. 6. The Image Overlay–I Java applet. (showing 1998 and 1999 ADAR images)

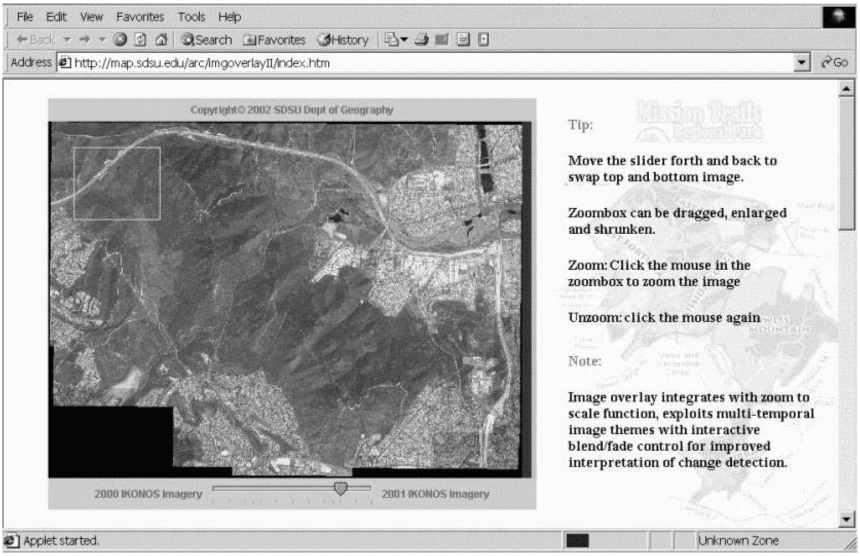

Fig. 7. The Image Overlay II Java applet (with flexible zoom-in capability)

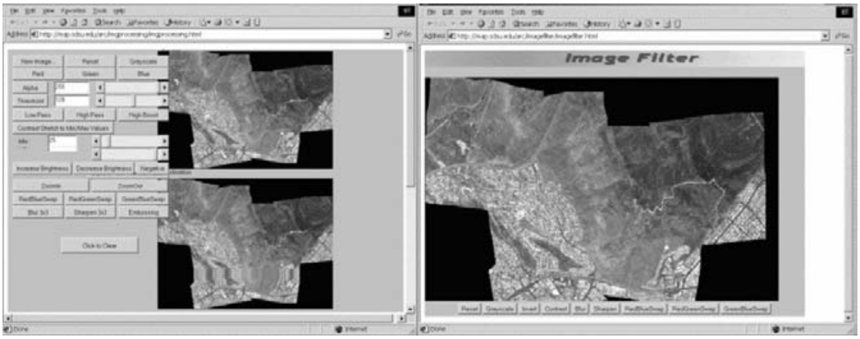

Fig. 8. The Image Processing Java applets

including image enhancement, zoom-in, zoom-out, image smoothing, image sharpening, image embossing, etc. The second Java applet provided the capability to display multi-band (RGB) or single-band (gray-scale) imagery.

This project demonstrated the feasibility of an image analysis toolbox. The demonstration toolbox contained multiple tools defined by eight different Java applets. Field tests of the toolbox demonstrated the potential capability of Web-based analytical tools to greatly aid resource and habitat managers through the analysis of for remote sensed images. Java programmers can easily customize these Java source codes to create new applications or combine additional functions. Several research projects and GIS/Remote Sensing vendors have already adopted Java as their principle development tool. For example, the GeoVISTA Studio developed at Penn State University (www.geovistastudio.psu.edu) is one successful example of adopting Java and component-based software engineering techniques to provide a visual programming environment for geoscientific data analysis and visualization (Takatsuka and Gahegan, 2002).

The previous sections of the paper have introduced an integrated Web-based GIS architecture that combining three levels of Web-based geographic information services (GIServices): data warehouses, Web mapping facilities, and Java-based image analytical tools. The next section describes the evaluation of the prototype Websites and their potential development for environmental monitoring and management.

6 Prototype evaluation and potential developments

A prototype system (http://map.sdsu.edu/arc) was developed using data warehouses, Internet map servers, and Java-based programming tools. The final task of this project was to test the prototype to evaluate the utility of its Web mapping functionality and analytical tools. The research team conducted two expert review sessions with GIS professionals, park rangers and GIS and remote sensing graduate students. Training tutorials for the prototype and evaluation questionnaires were formatted as standardized PDF files and HTML documents and were posted on the project Web site. Posting project documentation allowed potential Web users access to the documents and the ability to respond to the questionnaire following their evaluation of the prototype system.

In general, the feedback from the evaluation team was very positive. All participants felt that the Web-based tools were useful for many of their day to day analysis tasks and clearly have a great potential for improving habitat management. The following key points were obtained from user feedback.

- The Web-based interfaces are easy to use (comparing to other GIS/Remote Sensing software).
- The data warehouse needs to clarify some metadata terminology.
- Internet map servers would benefit from more detailed temporal or seasonal information about remotely sensed images and GIS layers.
- Web-based tools have great potential as an information resource for Mission Trail Regional Park visitors and the public.
- Viewing and querying GIS data layers was difficult while remotely sensed image were in the background (via ArcIMS HTML viewers).

Based on the user feedback and the discussions between evaluators and the research team, two potential enhancements were identified for application to environmental conservation and habitat monitoring.

The first application enhancement addresses long term change detection and habitat monitoring needs. Web-based display of multiple-year remotely sensed imagery can clearly indicate long term temporal changes of land cover and vegetation. Combined with the GIS layers and spatial analysis functions, researchers can focus on long term changes in specific habitat areas for future investigation. From a park ranger's perspective, Web-based remote sensing tools can provide important visual clues as to where and when changes are taking place (change detection). On-line GIS analytical functions can then be used to determine causes (why) and assist in generating possible solutions for environmental protection and management tasks (how).

The second enhancement addresses the desire to combine Web-based GIS and remote sensing tools with Global Positioning System (GPS) and mobile devices (Pocket PC or PDA). Evaluator comments repeatedly expressed the belief that resource managers working in field environments would benefit from the use of mobile GIS applications (such as ArcPad or MapXtend) to access remotely sensed imagery and Web-based GIS via Wi-Fi wireless communication network. Natural habitat preservation managers and scientists can undertake habitat monitoring and change detection tasks in real time and submit their field observations and reports back to their organization's Web servers in near-real time. By integrating GPS, wireless communication, Web-based GIS and remote sensing tools, park rangers and other resource mangers can optimize their field-based management tasks significantly improving field operations efficiency. One such mobile GIS prototype application has been initiated recently at San Diego State University (http://map.sdsu.edu/mobilegis).

7 Conclusions

This research and the prototype Web site have demonstrated the potential and opportunities afforded by the integration of Web-based GIS and on-line remote sensing facilities for environmental monitoring and management. The integration of Web-based GIS and remote sensing tools offers significant benefits over traditional field survey methods associated with resource and habitat management duties. Traditional approaches for accessing very large volumes of remotely sensed imagery are time-consuming and problematic. Only experienced users with sufficient software training can access geospatial data and imagery through use of complicated GIS and Remote Sensing software. Before the advent of Web-based GIS, expensive GIS and Remote Sensing software packages, complicated software installation, and the lack of software training prevented regional park rangers and local natural resource managers to utilize the power of GIS and Remote Sensing. By adopting Web-based GIS and on-line remote sensing facilities, natural resource managers or regional park rangers can access valuable geospatial information and images for their daily tasks without the challenge and cost of upgrading GIS and image processing software on their local computers.

In summary, Web-based GIS and on-line imagery analysis tools provide a flexible way to access, extract and create spatial information essential for environmental monitoring tasks. The need for a capability to monitor natural preserves using simple change detection methods is worldwide and is fundamental to cost-effective management practices. This paper has introduced an integrated Web-based GIS architecture by combining three levels of GIServices: data archive, information display, and spatial analysis. An on-line data warehouse was developed for archiving, accessing and downloading both GIS databases and remotely sensed imagery. Multiple interactive map servers and image servers were established to provide Web-based mapping functions for the display of land use, vegetation, soil, trails, roads, and remotely sensed images. Java-based on-line analytical tools (Java applets) provided advanced image comparison and analysis functions for land cover change detection. This paper also discussed the major challenges to integrating Web-based GIS and on-line image analysis tools, including metadata standards, data transmission formats, communication protocols, client/server balance, and ubiquitous access. Hopefully, these problems will be solved and the challenges answered by continued collaborations between the GIS and Remote Sensing communities in the foreseeable future.

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