Microsoft TerraServer: A Spatial Data Warehouse

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ABSTRACT

Microsoft® TerraServer stores aerial, satellite, and topographic images of the earth in a SQL database available via the Internet. It is the world's largest online atlas, combining eight terabytes of image data from the United States Geological Survey (USGS) and SPIN-2. Internet browsers provide intuitive spatial and text interfaces to the data. Users need no special hardware, software, or knowledge to locate and browse imagery. This paper describes how terabytes of "Internet unfriendly" geo-spatial images were scrubbed and edited into hundreds of millions of "Internet friendly" image tiles and loaded into a SQL data warehouse. All meta-data and imagery are stored in the SQL database. TerraServer demonstrates that general-purpose relational database technology can manage large scale image repositories, and shows that web browsers can be a good geo-spatial image presentation system.

Keywords

Geo-spatial, VLDB, image databases, internet.

1. Overview

The TerraServer is the world's largest public repository of high-resolution aerial, satellite, and topographic data. It is designed to be accessed by thousands of simultaneous users using Internet protocols via standard web browsers. TerraServer is an image "tile" server that delivers a set of raster images based on a users search criteria. Once an image of interest is located, users can pan, zoom in, zoom out, or display meta-data about the image they are viewing.

The TerraServer is a multi-media data warehouse. It differs from a traditional data warehouse in several ways: (1) it is accessed by millions of users, (2) the users extract relatively few records (thousands) in a particular session and, (3) the records are relatively large (10 kilobytes). By contrast, classic data warehouses are (1) accessed by a few hundred users via proprietary interfaces, (2) queries examine millions of records, to discover trends or anomalies, (3) the records themselves are generally less than a kilobyte. In addition, classic data warehouse queries may run for days before delivering results. Initial results typically cause users to modify and re-run queries to further refine results.

One thing the TerraServer has in common with classic data warehouses is that both manage huge databases: several terabytes of data. TerraServer's topographic maps cover all of the United States at 2 meter resolution 10 million square kilometers), the aerial photos cover 40% of the United States today (3 million square kilometers) at one-meter resolution, and 1% of the urban areas outside the United States (1 million square kilometers) at 2 meter resolution.

This report describes the design of the TerraServer and its operation over the last 18 months. It also summarizes what we have learned from building and operating the TerraServer.

Our research group explores scaleable servers. We wanted first-hand experience building and operating a large Internet server with a large database and heavy web traffic. To generate the traffic we needed to build an application that would be interesting to millions of web users.

Based on our exposure to the EOS/DIS project [2], we settled on building a web site that serves aerial, satellite, and topographic imagery. We picked this application for four reasons:

1. The web is inherently a graphical environment, and these images of neighborhoods are recognizable and interesting throughout the world.

2. We believed this application would generate the billions of web hits needed to test our scalability ideas.

3. The data was available. The USGS was cooperative, an since the cold war had ended, other agencies were more able to share satellite image data. The thaw relaxed regulations that had previously limited the access to high-resolution imagery on a global basis.

4. The solution as we defined it – a wide-area, client/server imagery database application stored in a commercially available SQL database system – had not been attempted before. Indeed, many people felt it was impossible without using an object-oriented or object-relational system.

This paper describes the application design, database design, hardware architecture, and operational experience of the TerraServer. The TerraServer has been operating for eighteen months now. We have deployed the third redesign of the database, user interface, and process of adding new images to the database.

2. Application Design

TerraServer is accessed via the Internet through any graphical web browser. Users can zoom and pan across a mosaic of tiles within a TerraServer scene. The user interface is designed to function adequately over low-speed (28.8kbps) connections. Any modern PC, MAC, or UNIX workstation can access the TerraServer using a standard web browser – Internet Explorer 3.0 or later, or Netscape Navigator 3.0 or later. If you have never used it, look at the TerraServer web site at http://terraserver.microsoft.com/.

There are four methods by which a user locates an image:

(1) **Coverage Map:** clicking on low resolution map of the world shaded to show where coverage exists,

(2) **Place Query:** entering a place name, e.g. San Francisco,

(3) **Coordinate Query:** entering the longitude and latitude of interest, or

(4) **Famous Place:** selecting a location from a pre-compiled list of places.

A successful search presents the user with a web page containing an HTML table of image tiles fetched from a SQL database. GIF images surrounding the image tile table provide the user with the following basic controls:

- Pan and zoom
- Display image meta data
- Download an image copy
- Control the size of the image table. There are three fixed sizes – Small (400 x 200 pixels), Medium (600 x 400 pixels), and Large (800 x 600 pixels).
- Choose the image "style" or theme. TerraServer stores three image styles -- imagery stored in TerraServer – shaded relief, topographic map, and photograph (aerial or satellite).

We expect and support the use of TerraServer image tiles on remote web sites. Most data on TerraServer is public domain data. Therefore, we deliberately chose simple graphics and storage methods so that users could craft their own web pages that display TerraServer image tiles.

Imagery is categorized into "themes" by data source, projection system, and image "style". Currently, there are four data themes:
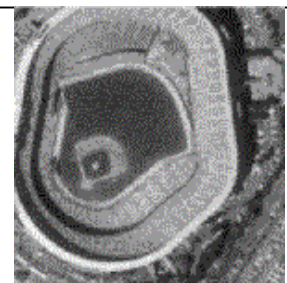

Figure 1. A USGS DOQ Image of 3Com Park near San Francisco

USGS Digital Ortho-Quadrangles (DOQ) are gray-scale or color infrared, 1-meter resolution aerial photos. Cars can be seen, but 1-meter resolution is too coarse to show people. Imagery is ortho-rectified to 1-meter square pixels. Approximately 50% of the U.S. has been digitized. The conterminous U.S. is expected to be completed by the end of 2001. Some locations have more than one DOQQ image available varying by image source date or color mode. TerraServer stores the latest grayscale image. If only a color infrared image is available, they it is converted to grayscale before tiling and storing in the database.

USGS Digital Raster Graphics (DRG) DRGs are the digitized versions of the popular USGS topographic maps. The complete set of USGS topographic maps have been scanned for the conterminous United States and Hawaii. The original images are available in three map scales – 24,000:1 (2.4 meters/pixel), 100,000:1 (10 meters per pixel) and 250,000 meters per pixel. The raster images are re-sampled to nearest power of 2 meters per pixel.
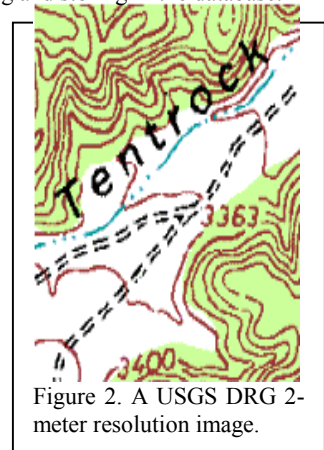

Figure 2. A USGS DRG 2-meter resolution image.

Aerial Images SPIN-2™ are grayscale 1.56-meter resolution de-classified Russian military satellite images. The images are re-sampled to 2-meter resolution. Terra-Server contains SPIN-2 images of Western Europe, the United States, and the Far East. Unfortunately, there is little coverage of Canada, South America, Africa, and Southeast Asia. The SPIN-2 imagery is rectified, i.e. rotated so north is up, but is not ortho-rectified. That is, the image is not "rubber sheeted" so that each pixel covers a consistent square number of square meters. However, given the height of the satellite, the difference in ground area between individual pixels is small.
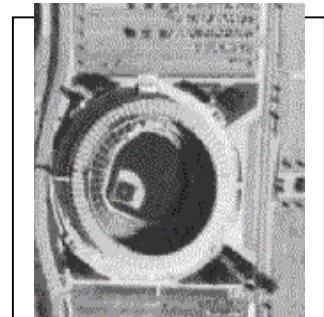

Figure 3. a SPIN-2: 1.56-meter image of Atlanta's Fulton County Stadium.

Encarta Shaded Relief is natural color, shaded relief map of the globe. The full resolution image detail is approximately 1 kilometer per pixel. The image is a seamless image of the globe between latitude +80º and -80º. The Microsoft Geography Business Unit assembled the image from a public domain combination of weather satellite data and elevation data. The image appears in the Encarta Virtual Globe add-on product to the Encarta Encyclopedia CD title.
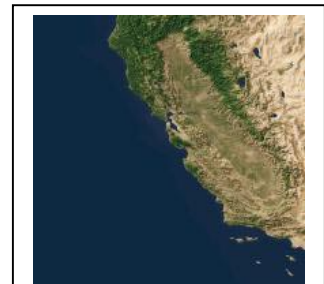

Figure 4: Encarta Virtual Globe shaded relief image of California, 8km / pixel.

2.1 System Architecture

TerraServer is a "thin-client / fat-server" design. The TerraServer has a 3-tier architecture:

Tier 1: *The Client* is a graphical web browser or other hardware/software system that supports HTTP 1.1 protocols and HTML 3.2 document structure. TerraServer is built and tested with Netscape Navigator and Internet Explorer on Windows, MacOS, and UNIX.

Tier 2: *The Application Logic* is a web server application that responds to HTTP requests submitted by clients by interacting with the Tier 3 database system and applying logic to the results returned.

Tier 3: *The Database System* is a SQL Server 7.0 Relational DBMS containing **all image** and meta-data required by the Application Logic tier.

Most web pages are dynamically formed and contain standard HTML 3.2 tags. All imagery is stored within SQL Server "blob fields" and compressed in Jpeg or Gif format. There is one row per image tile. The row contains the meta-data describing the tile's geographic attributes and one blob field containing the image data. Imagery is presented via <IMG SRC=…> tags without the aid of java applets, or other specialized client side controls. The SRC URL references a script executed on the web server that is fetched from the database and sent back to the browser prefixed with the appropriate mime type. TerraServer supports Netscape Navigator and Internet Explorer V3.0 or later browsers.

"Zoomed out" or sub-sampled imagery is also stored in the database, one-row per tile. Four higher resolution tiles are sub-sampled into one lower resolution tile. The process is repeated for the number of levels in the image hierarchy. We found, and our graphics colleagues have confirmed, that a 7 level image pyramid is the maximum for grayscale imagery. All levels of the image pyramid are pre-computed and stored in the database for the following reasons:

1. We wanted to build the largest physical database that we could.

2. A 7 level image pyramid would require 25,600 tiles to be sub-sampled to create one single 64:1 resolution tile. We do not believe users are willing to wait for this operation to be completed "on-the-fly".

3. We did not have the resources to develop and support a high performance, server-side sub-sampling and dynamic image generation application.[1]

4. We wanted users to reference TerraServer imagery on their own web pages with a simple <IMG SRC…> tag and not require a client-side control to display and sub-sample the imagery.

The web site is a cluster of machines. A set of servers executes Microsoft Internet Information Server (IIS) web server software that interfaces with the SQL Server databases. The site is designed to support a variable number of web servers for performance (more net cards for increased bandwidth) and reliability reasons (a failed web server does not take down the whole web site). Increasing the throughput of the web site is as simple as adding another web server until the network web and database servers saturate.

The web servers connect to the database servers that host the SQL Server database via a separate internal network. This protects the SQL Servers provides an extra level of security from hackers and a separate private network that does not compete with Internet or other network traffic. Currently, there are two database servers – one for aerial and satellite imagery, and a second for the topographic maps. There are also two 100mbit subnets between the database and web servers.

The number and size of database servers is determined by the popularity of the data and convenience. The bandwidth between database servers and web servers drives the hardware configuration. Topo maps are expected to be popular, so we decided to host them on a separate machine where queries for aerial photography data do not have to compete for bandwidth with queries for topo data. The shaded relief data is small and replicated on both the topo and aerial photography server.

Web pages containing imagery have a consistent layout. Users can control the number of image tiles that appear on a single page. The user's monitor size and Internet connection speed dictate their choice. Web pages are dynamically created on the web servers due to the millions of combinations of possible web pages.

There are a wide number of choices for dynamic web page construction on Internet Information Server based web servers – ISAPI, Active Server Pages, CGI/Perl, Cold Fusion, etc. We chose Active Server Pages (ASP) for a number of reasons:

- Fast and easy development – ASP host Visual Basic or JavaScript engines. An ASP document can be written and debugged without requiring a compiler or other elaborate development tools.

- The execution time of our ASP scripts was dominated by the SQL execution time and the data transfer time between database and web server. There was little or no performance gain in using a compiled language.[2]

We chose Visual Basic as the scripting language because it had better support for error handling. The Active Data Object (ADO), an OLEDB object, is used to access the SQL Server database engine. The Visual Basic error object could trap the errors raised by the ADO object. Our Visual Basic scripts process URL query strings, access the Imagery SQL database, and dynamically generate HTML pages. One ASP page, Tile.asp, is responsible for retrieving Jpeg or GIF formatted blobs from the database and sending it back to the client. A second ASP page, image.asp, is responsible for executing SQL queries to fetch the meta data necessary to dynamically produce the HTML tags which format an image page. These two web scripts are called 85% of the time.

The Cmap.asp (coverage map), Place.asp, Geo.asp, and Famous.asp implement the four search methods described

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[1] The entire TerraServer web and database application was developed by one person.

[2] Originally we built the web application in C and accessed the web server via the ISAPI interface. We abandoned this approach after determining there was no performance gain in our case and a substantial increase in development cost.

previously. Each major function, e.g. Download, Image Information, the Home Page, etc., is implemented by a separate ASP page.

All TerraServer ASP scripts have a common structure. Database access is performed by calling a single SQL Server stored procedure function. The SQL stored procedure returns one or more record sets. The ASP script calls ADO methods to connect to the database server, call one stored procedure, iterate through the returned result set(s), and disconnect. This design achieves the highest performance as we learned during the first few weeks of service.

2.2 Tuning the Application

TerraServer was our group's very first web site. While we had some professional graphics design assistance, we developed the web application by the classic seat-of-the-pants method. Also like most software projects, particularly Internet projects, we were under marketing pressure to release to the web quickly. We learned a lot about our design and products we chose during an all too brief beta period and during the first month of live service.

We initially estimated the application was interesting enough to generate 1 million hits or 250,000 page views a day. Later we increased our estimate to 5 million hits and 1 million page views a day. We configured 4 web servers to support the 5 million hits and 1 million page views per day estimate. Officially, TerraServer went live on June 24, 1998. However, there was an article published on the front of the USA Today Business page on June 22, 1998. The article proved we grossly underestimated the popularity of the web site.

Starting on June 22, our four web servers managed to deliver 35 million web hits and 8 million page views. Millions more were rejected. We quickly grew our site to 10 web servers by the weekend and learned the following:

1. Web server software is really a TP Monitor. Once we realized this point, we used the tuning skills we learned back in the late 70s and 80s to good use. We treated the database server as a scarce resource and used the web server configuration tools to optimally schedule requests to the back end. Prior to this discovery, we unleashed requests from the web servers to the backend via a "fire hose" and were genuinely surprised when the database server ground to a halt.

2. Round trips to the database server are costly. Therefore, do as much as possible in one trip.

3. People look at imagery of where they live. While spending many a sleepless night the first week, we noticed that there was the interesting "sine wave" of Internet connection and disk activity. In highly populated and covered areas, we would notice a precipitous rise in user connections at the start of that time zone's day. Between 5 am and 6am PST or 8 am and 9am EST, the number of user connections would rise steeply. About one hour later, the number of connections continued to rise, but the disk activity began to drop and reach a steady state. Over time, we realized that separate users were requesting the same data as their neighbors. We had 2 GB of physical memory on the database server, about 1.8 GB was SQL Server's memory cache. Thus many of the queries were

resolved out of the database cache.

Over time, we realized the TerraServer web site is busiest in the mornings where we have coverage. Thus our web site is very active from 11pm to 3 am (Europe) and from 5 am to 3 or 4 pm. But it is not very busy around 5 pm because we have very little coverage in the Pacific Rim and East Asia.

4. Our Microsoft.com and msn.com colleagues confirmed some other web usage facts. The internet is busiest on Mondays and Tuesdays. Saturday and Sunday is half the volume of Monday and Tuesday. A steady slide occurs from Wednesday thru Friday. Thus, we do on-line database maintenance on the weekends – on-line backups, table reconfigurations, etc.

2.3 Scenes and Projection Systems

TerraServer is map and image data tiling system. Unlike online mapping web sites, e.g. MapQuest, TerraServer does not re-project the data to match the user's request. Instead, TerraServer displays the image or topographical map data in the projection chosen by the data provider.

TerraServer allows a user to navigate the length and width of an entire scene. A web page contains tiles from only one scene. Lists of links to scenes that overlap the viewed scene are offered to the user. Thus TerraServer really is a collection of seamless scenes and not a single seamless view of earth.

The reason for this is geometry and geography. The earth is a bumpy ellipsoid. Maps and computer monitors are flat. It is impossible to accurately present a spherical object on a flat surface.

Cartographers have addressed this issue by developing projections of the geoid onto flat surfaces [5]. There are many projection systems, each suited to present certain regions or properties. Multiple images in a projection system can often be joined together to form a seamless mosaic within certain boundary conditions. These mosaics either have extreme distortion as they scale out, or they introduce seams.

DOQ and DRG data are projected by the USGS into Universal Transverse Mercator (UTM) projection using the North American Datum (NAD) ellipsoid created in 1983 [7]. UTM is a projection system that divides the earth into 60 wedge shaped *zones* numbered 1 thru 60 beginning at the International Date Line. Each zone is 6 degrees wide and goes from the equator to the poles. UTM grid coordinates are specified as zone number, then meters from the equator and from the zone meridian[3].

The conterminous United States is divided into 10 zones (see Figure 5). Each of these UTM zones is a *scene*. The TerraServer mosaics each scene, but two adjacent scenes are not mosaiced together. Users can pan and zoom within a scene, and can jump from one scene to another.

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[3] Actually, UTM grid units can be in inches, feet, meters, or kilometers. The USGS chose meters for most of their assets in the UTM projection. UTM is not used above 80N or 70S [5].

Figure 5: The ten UTM zones in the continental United States.
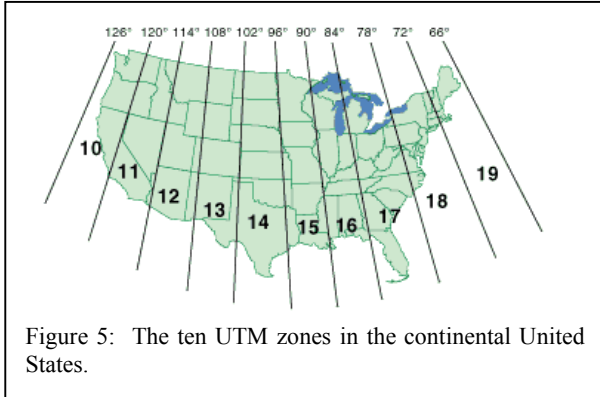
The SPIN-2 imagery is digitized from Russian satellite photographs. The Russian satellite captures 160km wide by 40km high areas in a single image. The satellite takes one image and then begins the adjacent image, overlapping the last image. The overlap is variable, and when digitized does not line up on a pixel boundary.

To create a seamless mosaic of SPIN-2 imagery, all SPIN-2 imagery would have to be ortho-rectified. This requires precise geo-location of each image, which was not available due to security concerns. Without rectification, if tiles extracted from separate SPIN-2 satellite images are mosaiced, the tile edges are misaligned. Roads, rivers, and other geographic features do not line up. While this may be understandable to GIS experts, it is disorienting and unacceptable to novice users.

Consequently, the TerraServer treats each 160km x 40km SPIN2 image as a separate scene. These scenes are not mosaiced together. Users can pan and zoom within a scene, and can jump from one scene to another.

2.4 TerraServer Grid System
Users can zoom and pan across a mosaic of tiles within a TerraServer scene. The tiles are organized in the database by theme, resolution, scene, and location within a scene in the TerraServer grid system.

TerraServer supports a fixed number of resolutions in powers of 2 from 1/1024 meters per pixel (scale 0) through 16384 meter per pixel (scale 24). One-meter per pixel is scale 10.

For UTM projection data sets, the SceneID is the UTM zone assigned to the original image a tile's pixels were extracted from. For SPIN2 data sets, a unique SceneID is assigned for each scene loaded per theme.

Each TerraServer scene is planar. A tile can be identified by its position in the scene. The tile loading program assigns a relative X and Y tile identifier to each tile as it is loaded.

For UTM projected data, the X and Y tile address is the UTM coordinate of the top-left most pixel in the tile divided by the tile image size in UTM units in meters. The following are the formulas:

$X = TopLeftUTM\_X / (TilePixWidth \bullet Resolution)$
$Y = TopLeftUTM\_Y / (TilePixHeight \bullet Resolution)$

For SPIN2 scenes, the X and Y tile addresses are relative to the upper left corner of the scene.

The six fields – Resolution, Theme, SceneID, Scale, X, and, Y - form the unique key by which any TerraServer image tile can be directly addressed. Each TerraServer web page contains image tiles from a single Theme, Scale, and SceneID combination. For example, our office building in USGS DOQ theme (T=1), has scene UTM zone 10 (S=10), at scale 1 meter (Z=10) with X=2766 and Y=20913. The URL is:
http://terraserver.microsoft.com/tile.asp?S=10&T=1&Z=10&X=2766&Y=20913.

The TerraServer search system performs the conversion from geographic coordinate systems to the TerraServer coordinate system. The TerraServer image display system uses TerraServer grid system coordinates to pan and zoom between tiles and resolutions of the same theme and scene.

2.5 Imagery Database Schema
Each theme has an Source Meta-data table. This table has a row for each image that is tiled and loaded into the TerraServer database. The *OrigMetaTag* field is the primary key. The meta-fields vary widely from theme to theme. Some of the meta fields are displayed by the Image Info Active Server Page (for example
http://terraserver.microsoft.com/imageinfo.asp?S=17&T=2&X=17&Y=122&Z=17&W=1&O=c28080a1&P=28+km+SW+of+Orlando%2C+Florida%2C+United+States

All the image tiles and their metadata are stored in an SQL database. One table is maintained for each (theme, resolution) pair so that tiles are clustered together for better locality. USGS DOQ supports resolutions from 1-meter resolution through 64-meter resolution. USGS DRG data supports 2-meter resolution through 128-meter resolution. SPIN supports resolutions from 1-meter to 64-meter.

Each theme table has the same five-part primary key:

- *SceneID* –individual scene identifier
- *X* – tile's relative position on the X-axis
- *Y* – tile's relative position on the Y-axis
- *DisplayStatus* – Controls display of an image tile
- *OrigMetaTag* – image the tile was extracted from

There are 28 other fields that describe the geo-spatial coordinates for the image and other properties. One field is a "blob type" that contains the compressed image.

These tile blobs are chosen to be about ten kilobytes so that they can be quickly downloaded via a standard modem (within three seconds via a 28.8 modem).

2.6 Gazetteer Database Schema

Figure 6: Gazetteer and Image Schema
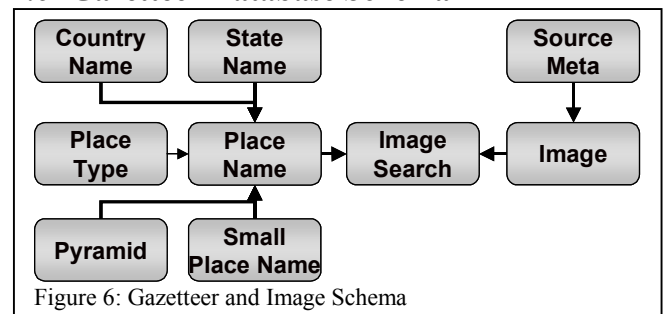
The Gazetteer lets users find images by name. It contains the names for about 1.5 million places, with many alternate spellings. It is a simplified version of the Gazetteer found in the Encarta Virtual Globe™ and Microsoft Streets™ products.

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