Summary of Revision

New materials (highlighted in paper) are added to address Reviewers' comments.

1. In Related Approaches (page 2): a short introduction to OpeNDAP, and the discussion of the gap between scientific data distribution and the needs of Earthquake response
2. In LOS profile tool (page 7): updated the LOS tool information and users participations in the development
3. In Conclusions and Future Work (page 11): added the short paragraph at the end on collaboration and social network with references
4. Figure 3 is updated to show the latest development of LOS profile tool
5. Added references to simplex and Virtual California
6. Minor English editing throughout, especially in Introduction

Using Service-Based Geographical Information System to Support Earthquake Research and Disaster Response

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Classification: Physical Sciences, Computer Sciences

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Abstract: As earthquake research has expanded beyond the geophysics community to include the requirements of rapid emergency response and disaster management, the computational infrastructure that supports this research must also expand to deliver both data and analysis tools to a wide variety of users. In this article, we investigate service-based Geographical Information System (GIS) technologies that enable an open-architecture cyberinfrastructure to provide standards-compliant data products and computing services for both earthquake research and disaster planning and response. We evaluate this framework with examples from two earthquake science projects: QuakeSim and E-DECIDER. Based on these case studies, we discuss gaps and research opportunities in further developing service-based GIS with the emerging Cloud Computing technology.

Keywords: GIS, Earthquake, Service-Oriented Architecture, Cloud Computing

Introduction

The high demand for international collaboration on rapid emergency response and disaster management from the recent major earthquake disasters in Haiti (2010) and Japan (2011) has put the study of earthquakes into a new perspective. These events demonstrate that geophysicists must both work effectively across research groups, and find ways to timely deliver their knowledge, tools, and results to emergency planners and responders. As participants in the emergency response efforts on Japan 2011 earthquake organized by International Charter (http://www.disasterscharter.org/), our experiences highlighted the lack of infrastructure for timely distributing and processing the huge amount of geospatial data for emergency response. It is important to build the computational infrastructure to support this transformation.

Service-Oriented Architecture (SOA) has gained great importance to build the support infrastructure to meet rapid changing needs. In terms of computing technology, services here are defined as "distributed components that have distinct functionality—especially functionality shared usefully among different uses" [1]. Service-based Geographical Information System (GIS) further develops Internet GIS using a SOA approach to enable sharing geospatial data as well as geo-processing tools among interested parties. Several desirable characteristics, such as increased flexibility and software reuse, make service-based GIS a useful framework to meet the growing needs of connecting earthquake research community and emergency responders. In this article, we concentrate primarily on the following two types of service (DaaS and SaaS), report our efforts on using service-based GIS technology in two related earthquake research projects (QuakeSim and E-DECIDER), and demonstrate the process of building on-line tools with two specific case studies (LOS profile tool and Simplex).

- Data as a Service (DaaS): Earthquake research involves numerous types of spatial data, such as seismicity, GPS time series and optical images. Many of these are distributed in file formats that are not widely supported outside the geophysics community. It is necessary to integrate data from multiple sources and produce standards-compliant geospatial products through DaaS. Also, DaaS must support the series of operations associated with the remote data, including projection support, format conversion, and data fusion.

- Software as a Service (SaaS): It is very common that earthquake researchers rely on in-house software packages to analyze a specific type of data. For example, QuakeSim project developed Daily Regularized Deterministic Annealing Hidden Markov Model (RDAHMM) packages [2] to analyze GPS daily time series data and the Simplex tool [3] to find a dislocation fault model that best accounts for observed GPS and InSAR deformation data. SaaS not only hosts the applications accessible through Internet, but also facilitates intuitive web interfaces for the broad range of end users if coupled with a well-designed service programming interface. Combined with DaaS, SaaS makes the in-house software outputs usable by downstream applications.

Related Approaches

On-line web mapping services, such as Google Map, Google Earth and Bing Map, have played important roles in making critical information more accessible around earthquake disasters. For example, Google Crisis Response project (http://www.google.org/crisisresponse/) has published large amount of high-resolution satellite images and maps of affected areas immediately after Japan (2011) earthquake. USGS earthquake program (http://earthquake.usgs.gov/) also produces many earthquake data products that can be directly displayed on Google Map. There are multiple ways to deliver data products through Google Map. One is to pack data inside KML/KMZ files, which is suitable for delivering small amount of static data, such as historical earthquake information. Other approaches, including GeoRSS feeds, generally require a server setup to stream the data dynamically from data providers. The latter is more suitable for emergence responses, since the data is constantly updated during disasters.

Such on-line web mapping service is reliable and efficient to deliver emergency response information to end users, and popular services like Google Map are well supported in GIS community. However, it doesn't provide a complete data distribution platform for earthquake emergency responders. Even though data products are well presented to general users, there is no corresponding data distribution service for emergency responders to directly pull third-party data out of Google Map or Bing Map. For example, after Japan (2011) earthquake, multiple agencies have made thousands of satellite images viewable though Google Map, yet emergency responders still have to download the image source files from original data providers separately to generate damage estimation mapping products. Different data providers often require different download mechanisms and protocols, and it quickly becomes a cumbersome task just to retrieve images already viewable on Google Map. Additionally both Google and Bing are closed system, and there is no easy way to supply third-party software service through their infrastructure.

On the other hand, various approaches and plenty solutions have been developed for data sharing and distribution within scientific communities. Inside Geophysics community, OpeNDAP (http://opendap.org) (Open-source Project for a Network data Access Protocol) makes seamless data sharing across Internet regardless of local storage format, and is widely used to distribute satellite, weather and other observed earth science data from various agencies such as NASA and NOAA. OpeNDAP clients include standalone tools, add-on packages and web applications. The target users of OpeNDAP are scientists, enabling them to integrate remote data sources into scientific applications. However, downstream platforms to deliver digested earthquake knowledge to broader range of end users and more general audiences are still lacking.

These limitations further motivate us to adopt the service-based GIS approach to provide both data and software services while utilizing on-line web mapping tools as the front interface to present final products.

QuakeSim and E-DECIDER Project

QuakeSim and E-DECIDER are NASA-funded earthquake research projects involving earthquake researchers and computer scientists from several research institutes. The goal of QuakeSim [4, 5] (http://www.quakesim.org/) is to couple multiple observation sources with both forward and inverse modeling applications for investigating both individual earthquake events and complex interacting fault systems. QuakeSim data sources include GPS, seismicity, geometric fault models, Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) and Interferometry Synthetic Aperture Radar (InSAR) images. Application codes include dislocation models (Disloc and Simplex), Geophysical Finite Element Simulation Tool (GeoFEST, http://www.openchannelsoftware.org/projects/GeoFEST), probabilistic forecasting tools (Virtual California [6]), and time series data mining tools (RDAHMM).

E-DECIDER (Earthquake Data Enhanced Cyber-Infrastructure for Disaster Evaluation) (http://www.e-decider.org/) is a downstream project that evolved from QuakeSim. It is a bridging effort to provide decision support for earthquake disaster management and response by utilizing NASA and other available remote sensing data in conjunction with the modeling software developed in QuakeSim project and other sources. The overall goal of the project is to deliver these capabilities as standards-compliant GIS data products through a web portal/web services infrastructure that is easy to use by decision-makers.

Serviced-Based GIS Architecture

The design of service-based GIS architecture aims to serve both data providers and end users through a series of web-services that are accessible through as many platforms as possible. Figure 1 shows a simplified architecture of service-based GIS systems. The right-hand side consists of clients, and the left-hand side is the server deployment, in which data collections (DaaS) and applications (SaaS) are made available through the virtual machine (VM) technology. The two major components of the GIS services (top left of Figure 1) are the implementations of various GIS core capabilities, and the more specialized Web Service layer that extends these for specific applications. VM gives the flexibility to meet the application run-time requirements, and each virtual machine can be configured to run only a certain type of service according to user demands.

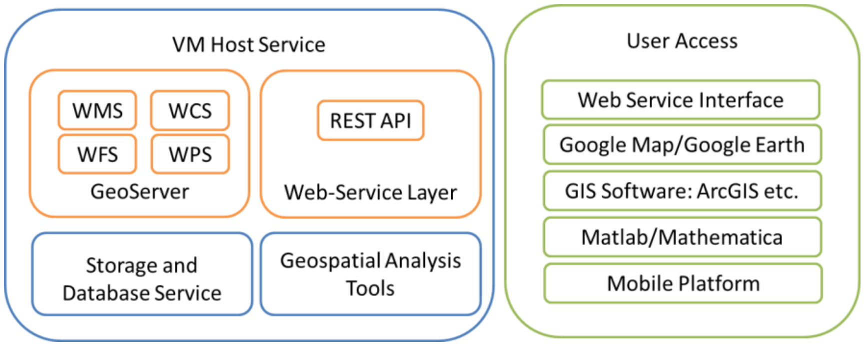

Figure 1 Service-based GIS Architecture

In our evaluations of service-based GIS, we choose GeoServer (http://geoserver.org) to provide core GIS capabilities of Figure 1. GeoServer is a community-maintained open source GIS server that allows users to share and edit geospatial data. It publishes data from any major spatial data source using the Open Geospatial Consortium (OGC) standards (http://www.opengeospatial.org/standards), which include the following:

- Web Map Service (WMS) is a standard for generating maps on the web for both vector and raster data, and rendering images in a number of possible formats: JPEG, PNG, GeoTIFF, GeoRSS, KML, and KMZ. The capabilities of WMS (and the corresponding GeoServer implementations) to handle these multiple output formats are very useful for building interactive user interfaces in our case studies.
- Web Coverage Service (WCS) provides a standard interface for requesting the raster source (raw images) and information over Internet. One of WCS most important capabilities is data subsetting, which is particularly useful for downstream applications that need to manipulate large imagery catalogs.
- Web Feature Service (WFS) is the interface for vector data sources, which include plotting definitions for features, such as geometrical definitions of earthquake faults, and extensions that can capture non-plotting metadata, such as earthquake slip rates and source descriptions.
- Web Processing Service (WPS) provides rules for standardizing inputs and outputs (requests and responses) for geospatial processing services. It is an efficient way to turn GIS processing tools into SaaS.

All of these basic OGC services expose network accessible request/response programming interfaces. However, it is usually useful to extend these generic interfaces. The Web Service layer provides easy-to-use network service (typically REST-based) API [7] for various specialized tasks. It can be both used in web applications and integrated into standalone applications that enable users to use the processing power of GIS server. It includes functionalities in the following categories:

- GIS Protocol Reflector API: GIS service request URLs (which must be constructed by clients in REST invocations) can be quite long and cumbersome. A reflector provides a much simpler URL call format. It also further enhances GeoServer to automatically adopt the configurations for different user platforms. For example, the URL to call a WMS to deliver KML that includes images in lower resolution format suitable for mobile platforms is http://server/wms?layer=layername&format=kml&target=mobile.

- Server-Service API: allows administrators to programmatically configure and manage the data and services on GIS server.
- Geoprocessing API: provides web interface for common GIS functionalities and other standalone analysis tools. It also handles the input/output of in-house applications that require specific data formats. It enables users to run a set of geoprocessing tools, including some computing intensive applications, in the distributed computing environment.

We have initially developed our GIS services on Indiana University Intelligent Infrastructure, which is based on VMWare vSphere software. Our prototype consists of a single virtual machine running 64-bit Red Hat Enterprise Linux Server (RHEL5) with 8GB RAM and 1TB disk space. It hosts the GeoServer and all necessary data for service-based GIS tools.

On-Line GIS Tools for UAVSAR Analysis

UAVSAR is a NASA project to use an uninhabited aerial vehicle (UAV) equipped with the synthetic aperture radar (SAR) system for rapid repeat-pass interferometry measurements of Earth's surface. The UAVSAR data portal (http://uavsar.jpl.nasa.gov/) distributes the SAR image products in the single-band binary files; the size of one single image ranges from several hundred megabytes to several gigabytes. It also supplies pre-rendered images stored as KML or KMZ, which can be visualized in Google Earth and Google Map. The disadvantage of this file-based distribution system is that users have to download the complete raw data and use special software capable of handling the UAVSAR format to analyze it. Without specific domain knowledge on SAR images, it is difficult for general users to extract useful information for emergency response.

We have developed GIS web services to automatically scan the metadata and import the SAR images into virtual storages. The images, after conversion to GeoTIFF, are distributed through WMS service; Figure 2 shows several examples. We also provide WCS services that allow users to access the raw data in the interested study area at user-specified spatial resolutions. UAVSAR ground-projected products are roughly 6 m x 6 m pixels in resolution; it is very common that users are only interested in the partial image at a much lower spatial resolution such as 30 m x 30 m rather than the whole original image. Through the on-demand WCS protocol, we can greatly reduce the burden of downloading large images to desktops and remote servers in distributed processing workflows and pipelines.

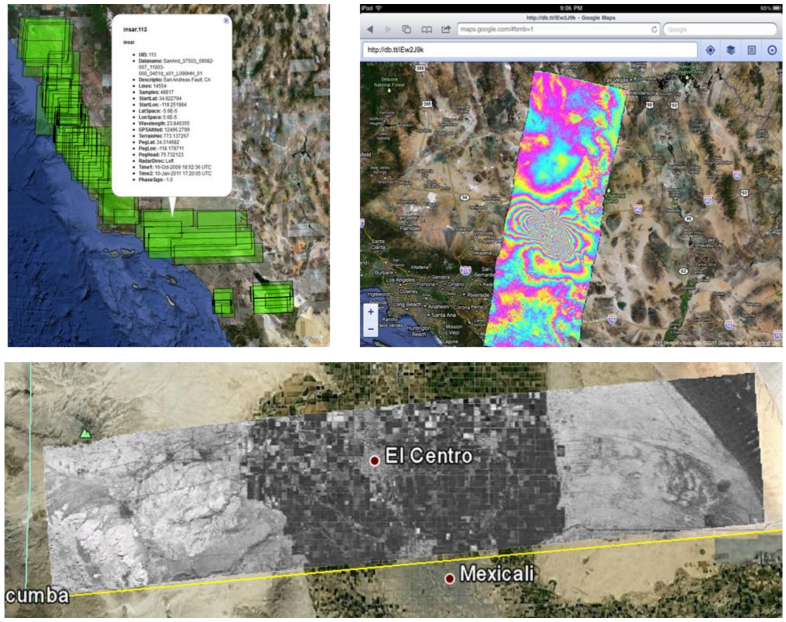

Figure 2 UAVSAR Distribution example, Image Metadata (top left), Image on mobile platform (top right), Google Earth (bottom)

In support of QuakeSim and E-DECIDER, we have built several on-line tools to help general users to analyze the UVASAR data directly through the web browser. We use the Line-Of-Sight (LOS) profile tool and the Simplex surface deformation inversion tool to demonstrate the structure of web applications based on GIS services. These examples show how powerful yet complicated GIS capabilities can be wrapped with simpler, application-specific APIs to build mash-ups and other third-party applications.

LOS profile tool is used to calculate the cross-section of Line-Of-Sight displacement in a SAR interferogram. We implement the required process to extract the LOS values from a selected SAR image as an add-on REST service co-deployed with GeoServer. The user interface (Figure 3) is implemented on a separate server using Google Map and JQuery JavaScript libraries.

In the first step, the user is presented with a map with thumbnails of all available data sets. The user clicks on the region of interest, and the server returns the list of images available in this area. Usually there are multiple overlapping images taken at different time periods, so we allow the user to refine the selection by presenting a table with all available images that contain the selected point (top right-hand side of Figure 3). The web service API for this operation has the form http://server/imagequery?location=lon1,lat1. Internally this service uses the WMS GetFeatureInfo function to query the vector layer that contains the bounding box and metadata of the InSAR images. Compared with the general and cumbersome WMS call URL, the web service API supplies a much simpler and cleaner interface to the web developer.

In the second step (lower half of Figure 3), the user is presented with a low-resolution version of the selected InSAR image. The user clicks on the map and is presented with draggable starting and ending points. The user drags the points on top of the selected image and is presented with interactive plots that show the value of LOS displacement and corresponding Digital Elevation Model (DEM) data along the cross section. These values are extracted from the high resolution data; the low resolution image shown in the Web interface is for presentation only. The service API has the form http://server/profiletool?image=image_id&points=lon1,lat1,lon2,lat2, with optional parameters including sampling method and resolutions. Internally, the wrapper service queries two images at the same time: one for the LOS calculation and the other for DEM. It generates a series of locations along the cross section, with the spatial sampling resolution decided by the balance between the plot quality and the length of the cross section or optional parameters. The profile tool service then calls the WMS GetFeatureInfo function for each location with the two images. LOS is calculated based on the query results from one of the images.

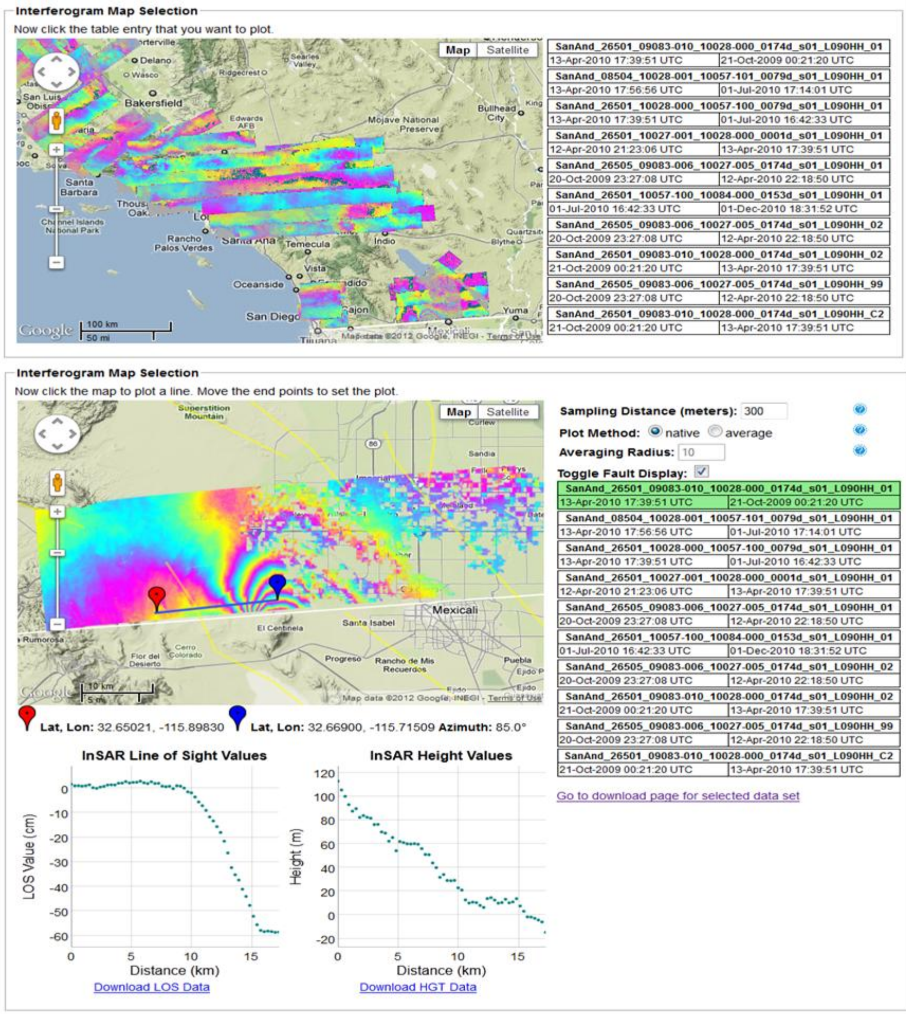

Figure 3 Screenshot of LOS profile tool: selection of images (step 1, top), LOS profile (step 2, bottom)

Users can access the development preview of LOS profile tool on QuakeSim website (http://www.quakesim.org/tools/los-profile-plotter). At the time of this article is written, 265 UAVSAR data sets are available, totaling about 1TB in file sizes. It includes both standard products distributed through UAVSAR data portal, and special-handling products with user-specific parameters supplied by internal collaborators. We currently support two sampling methods: native and average. Users can request both customized data products and additional sampling methods such as moving average to be integrated.

Simplex is a command line tool developed by collaborators at NASA JPL that optimally finds a dislocation model of fault slip that accounts for observed GPS and InSAR deformation data. In this case, we need to provide a separately running Simplex service (not co-located with our GIS services) with a subset of the observational data in a selected region of interest. It is possible to transfer the entire image file or files, but this is not optimal since Simplex only needs to be applied to a subset of the data (such as the region of interest showing displacement fringe patterns associated with an earthquake). Figure 4 shows the structure of the on-line Simplex tool. The user examines the high resolution interferogram image on Google Map through GeoServer WMS protocol. The polygon coordinates *n* of the user-selected region is sent as the parameter to the web service, http://server/simplex?image=image_id&polygon=lon1,lat1|lon2,lat2...|lonn,latn. The service is implemented as a python wrapper that pulls the data in the selected polygon region through the WCS protocol and generates the metadata file required by the command line Simplex binary; it also reformats the outputs for the plotting service. The plotting service produces a KML file that contains the Disloc interferogram generated from the estimated fault slip model and sends the result back to the web interface. Users can also programmatically call the Simplex Web Service API directly to process multiple studies on GIS server and avoid downloading the data and running the Simplex tools on the local computing resource. The Simplex tool itself is also under continuing development as new features are added. By providing Simplex as a service, we can ensure that the user always accesses the latest version. Version information is also part of the standard output of the service.

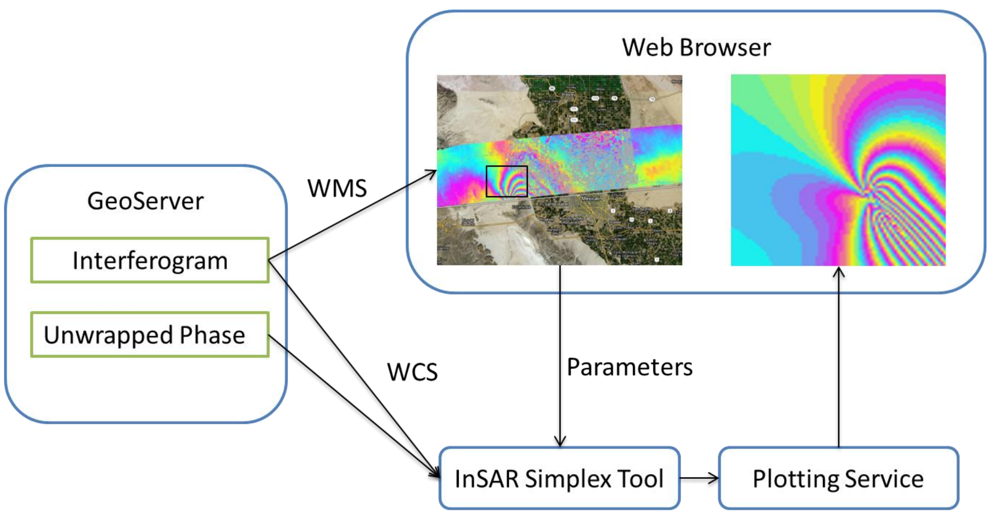

Figure 4 Structure of Simplex Tool

GIS Services for Emergency Response

The NASA-funded E-DECIDER project bridges the earthquake research and emergency response communities. The data products and tools from QuakeSim project are integrated with a broader range of services and workflows used by emergency responders. The service-based GIS system for the QuakeSim project provides the infrastructure services for the E-DECIDER project. Geophysical modeling tools and results of earthquake forecasting tools from QuakeSim project along with remote sensing data are accessible through Web Service APIs. One of the services is HAZUS gadget, which allows users to generate scenario earthquakes for FEMA (Federal Emergency Management Agency) HAZUS based on the forecasting results from QuakeSim. FEMA HAZUS (http://www.fema.gov/plan/prevent/hazus/) is a nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricanes. Emergency planners identify the interested region with the information from the forecasted hot-spot areas, which are provided by the global forecast of future earthquake activity service from the Open Hazards Group (http://www.openhazards.com/). Fault model parameters are currently determined using a simple heuristic method based on the magnitude of the earthquake event, but we can also obtain fault models through QuakeSim's QuakeTables service. Then the Web Service uses the OpenSHA framework [8] (http://www.opensha.org/) to generate the HAZUS input files for scenario earthquakes, which can be used for earthquake damage estimations. The simulation results can be shown on Google Map with the UAVSAR data to identify areas where the greatest deformation and damage has occurred and emergency services may need to be focused. Figure 5 shows the example of HAZUS gadget. Besides delivering both the products and web services through the E-DECIDER portal, we plan to further integrate serviced-based GIS system with the FEMA Unified Incident Command and Decision Support (UICDS) framework. UICDS (http://www.uicds.us/) is information sharing middleware for FEMA NIMS (National Incident Management System) incident management that continuously receives and shares standardized data among many agencies during an incident.

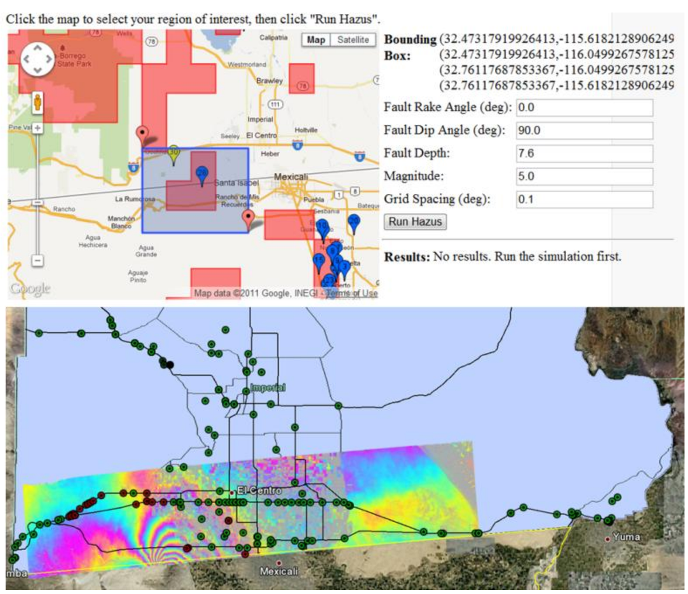

Figure 5 HAZUS gadget, hot spot forecast and fault model (top) and HAZUS simulation result (bottom, red dots indicate damaged bridges)

Conclusions and Future Work

This article presents the first steps of building the necessary infrastructure for the growing needs of collaboration efforts for earthquake research and disaster response. We use service-based GIS technology to build the platform for earthquake researchers to efficiently explore large amount of data (particularly GeoTIFF-encoded SAR imagery). It also gives researchers the tools to deliver their knowledge in a timely manner to emergency planners and responders. However, many gaps still need to be addressed with future research and development as outlined below.

The computing resource, network bandwidth and latency requirements of QuakeSim and E-DECIDER tools as well as data products after large earthquake events are uncertain. Developing countries have much less data, especially the pre-earthquake data, when compared with developed countries, as we have seen in Haiti 2010 and Japan 2011 earthquakes. The supporting computational infrastructure demands elasticity, and it is more than just starting up multiple virtual machines attached to a large storage. The Cloud Computing technology provides a more advanced on-demand computing deployment solution.

Cloud Computing [9, 10] provides elastically provisioned computing, software, and service infrastructure, typically implemented on a foundation of virtual machine and virtual data storage technologies. Commercial offerings include the Amazon Web Services suite (S3, EC2, EBS, and many others), Microsoft Azure, Rackspace, and Google App Engine. Open source software for building clouds includes OpenStack (http://openstack.org), Eucalyptus (http://www.eucalyptus.com), Nimbus (http://www.nimbusproject.org) and OpenNebula (http://opennebula.org/). Prominent cloud research efforts include NASA's Nebula and the NSF's FutureGrid. This elasticity allows users to outsource their computing infrastructure, growing or shrinking it as necessary.

Service-based GIS applications are based on open standards and not limited to the specific GIS packages and operating systems. They can be dynamically deployed as virtual appliances on top of advanced IT infrastructures, making cloud a natural fit for the emergency response, since the infrastructure usage levels are very low on average but spike immediately after earthquake events. In addition, with national or global-scale replication and content distribution, Infrastructure as a Service (IaaS) can provide distributed researchers and responders access to application servers with better network connections than particular centralized servers, as well as dynamic routing to the best available service instances.

We have designed the GIS server as the cloud-ready virtual appliances from the beginning. Our future work includes developing additional cloud-specific features on the service-based GIS framework, and migrating from basic VM hosting platform to the cloud infrastructure. So that once an earthquake happens, data providers can supply virtual images packed with the essential data and software that can be deployed automatically or instantiated by emergency responders on a cloud.

The earthquake response involves a variety of institutes and agencies; it is inevitable that complex policy issues, in regards of data security, sovereign and privacy, have significant impacts on system design and execution. For example, distributed geospatial data that are already hosted on private clouds can be collected and managed by catalog applications, such as GeoNetwork (http://geonetwork-opensource.org/). GeoSever supports loading data from remote WFS and WMS servers; the data pulled from the remote server can be cascaded through GeoServers and web services, providing a straightforward way to exchange the data among data providers. However, there is no clear mechanism to control the behavior of data cascading services, and this becomes especially complicated when it comes to geospatial data covering sensitive areas/targets. Many such complex issues related with hybrid public/private clouds are yet to be explored.

Currently our development efforts focus on building computational infrastructure to deliver data and tools from scientists to users. It is equally important to provide a collaboration platform that end users can directly communicate with scientists. With our approach of using standard web service and GIS protocols, we can further develop on-line tools as social-network-enabled gadget components that can support interoperable collaborations, and build web-based collaborative environment integrated with social media or science gateways [11, 12].

Acknowledgments

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Indiana University, University of Southern California, and University of California's Davis and Irvine campuses under contract with NASA. The work was sponsored by NASA's Advanced Information Technologies Program and Applied Sciences Program.

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