Using Service-Based GIS to Support Earthquake Research and Disaster Response

Service-based geographic information system (GIS) technologies can enable an open-architecture cyberinfrastructure to provide standards-compliant data products and computing services for both earthquake research and disaster planning and response. Here, a service-based GIS framework is evaluated using examples from two earthquake science projects: QuakeSim and E-Decider.

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

Service-oriented architectures (SOAs) have gained great importance as a way to build a support infrastructure that can meet rapidly changing needs. In terms of computing technology, we define services here as "distributed components that have distinct functionality—especially functionality shared usefully among different uses."[1] Service-based geographic information systems (GIS) further develop Internet GIS using an SOA approach to enable sharing geospatial data and geoprocessing tools among interested parties. Several desirable characteristics, such as increased flexibility and software reuse, make service-based GIS a useful framework for connecting the earthquake research community and emergency responders.

In this article, we concentrate primarily on two types of services—data as a service and software as a service (DaaS and SaaS)—and report on our efforts to use service-based GIS technology in two related earthquake research projects (QuakeSim and Earthquake Data Enhanced Cyber-Infrastructure for Disaster Evaluation, or E-Decider). We also demonstrate the process of building online tools for disaster response and data sharing with two specific case studies—the Line of Sight (LOS) profile tool and Simplex. To read more about others' work in this area, see the sidebar, "Related Approaches for Disaster Response and Data Sharing."

DaaS and SaaS

Earthquake research involves numerous types of spatial data, such as seismicity, GPS time series,

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Related Approaches for Disaster Response and Data Sharing

Online Web mapping services—such as Google Maps, Google Earth, and Bing Maps—have played important roles in making critical disaster response information more accessible. For example, the Google Crisis Response project (www.google.org/crisisresponse) published a large amount of high-resolution satellite images and maps of affected areas immediately after the 2011 Japan earthquake. The US Geological Survey's earthquake program (http://earthquake.usgs.gov) also produces many earthquake data products that display directly on Google Maps. There are multiple ways to deliver data products through Google Maps. One is to pack data inside Keyhole Markup Language and Keyhole Markup Zip (KML/KMZ) files, which is suitable for delivering a 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 emergency responses because the data is constantly updated during disasters.

Online Web mapping services are reliable and efficient to deliver emergency response information to end users, and popular services such as Google Maps are well supported in the GIS community. However, Google Maps doesn't provide a complete data-distribution platform for earthquake emergency responders. Even though data products are easily available to general users, there's no corresponding data-distribution service for scientists and emergency responders to directly pull third-party data out of Google Maps or Bing Maps. For example, after the 2011 Japan earthquake, multiple agencies made thousands of satellite images viewable through Google Maps, yet emergency responders still had 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 that are already viewable on Google Maps. Additionally, both Google and Bing are closed systems, and there's no easy way to supply third-party software services through their infrastructures.

On the other hand, various approaches and many solutions have been developed for data sharing and distribution within scientific communities. In the geophysics community, the Open Source Project for a Network Data Access Protocol (OpeNDAP; http://opendap.org) makes data sharing seamless across the Internet—regardless of the local storage format—and is widely used to distribute satellite, weather, and other observed earth science data from various agencies such as NASA and the National Oceanic and Atmospheric Administration (NOAA). OpeNDAP clients include stand-alone tools, add-on packages, and Web applications. The target users of OpeNDAP are scientists, who can use it to integrate remote data sources into scientific applications. However, we still lack downstream platforms that deliver digested earthquake knowledge to a broader range of end users and more general audiences.

These limitations further motivate us to adopt a service-based GIS approach to provide both data and software services while utilizing online Web-mapping tools as the front user interface to share expertise and knowledge among earthquake study groups and emergency responding communities.

and optical images. Many of these are distributed in file formats that aren't widely supported outside the geophysics community. It's 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 remote data, including projection support, format conversion, and data fusion.

Earthquake researchers often rely on in-house software packages to analyze a specific data type. For example, the QuakeSim project (www.quakesim.org) 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 Interferometry Synthetic Aperture Radar (InSAR) deformation data. SaaS not only hosts applications that are accessible through the Internet, but also facilitates intuitive Web interfaces for a broad range of end users, coupled with a well-designed service programming interface. Combined with DaaS, SaaS makes in-house software outputs usable by downstream applications.

QuakeSim and E-Decider Projects

QuakeSim and E-Decider (www.e-decider.org) are NASA-funded earthquake research projects involving earthquake researchers and computer scientists from several research institutes. The goal of QuakeSim[4,5] 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, and

Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) and InSAR images. Application codes include dislocation models (Disloc and Simplex), a Geophysical Finite-Element Simulation Tool (GeoFEST, www.openchannelsoftware.org/projects/GeoFEST), probabilistic forecasting tools (such as Virtual California[6]), and time series event-classification tools (such as RDAHMM).

E-Decider is a downstream project that evolved from QuakeSim. It's 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 the QuakeSim project and elsewhere. The project's overall goal is to deliver these capabilities as standards-compliant GIS data products through a Web portal/Web services infrastructure that's easy for decision makers to use.

Serviced-Based GIS Architecture

The design of a 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. Figure 1a is the server deployment, in which data collections (DaaS) and applications (SaaS) are made available through virtual machine (VM) technology. Figure 1b consists of clients. The two major components of the GIS services (top left of Figure 1a) are the implementations of various GIS core capabilities and the more specialized Web services layer that extends these for specific applications. VM gives the flexibility to meet the application runtime requirements, and we can configure each VM to run only a certain type of service according to user demands.

As Figure 1 shows, in our evaluations of service-based GISs, we use GeoServer (http://geoserver.org) to provide core GIS capabilities. GeoServer is a community-maintained, open source GIS server that lets users share and edit geospatial data. It publishes data from any major spatial data source using Open Geospatial Consortium (OGC; www.opengeospatial.org/standards) standards, including the ones listed here.

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. The ability of WMS (and the corresponding GeoServer implementations) to handle these multiple output formats was quite useful for building interactive user interfaces in our case studies.

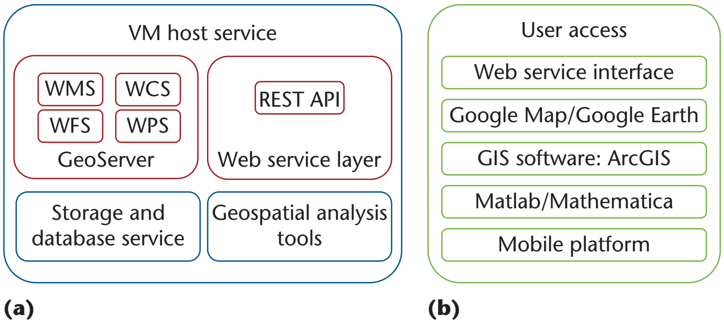


Figure 1. Service-based geographic information system (GIS) architecture. (a) Server deployment and (b) client access. The design aims to serve both data providers and end users through a series of Web services that are accessible through as many platforms as possible. WMS = Web Map Service; WCS = Web Coverage Service; WFS = Web Feature Service; and WPS = Web Processing Service.

Web Coverage Service (WCS) provides a standard interface for requesting the raster source (raw images) and information over Internet protocols. One of WCS's most important capabilities for our applications 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 for extensions that can capture nonplotting 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's an efficient way to turn GIS processing tools into SaaS.

All of these basic OGC services expose network-accessible request and response programming interfaces. However, it's typically useful to extend these generic interfaces. The Web service layer provides an easy-to-use network service (typically based on the representational state transfer, or REST) API for various specialized tasks.[7] It can be used in Web applications and integrated into stand-alone applications that let users harness the GIS server's processing power. Thus, the Web service layer includes functionalities in the following three 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 Keyhold Markup Language

(KML) that includes images in a lower-resolution format suitable for mobile platforms would be http://server/wms?layer=layername&format=kml&target=mobile.

Server–service API. This lets administrators programmatically configure and manage the data and services on the GIS server.

Geoprocessing API. This provides a Web interface for common GIS functionalities and other stand-alone analysis tools. It also handles the input/output of in-house applications that require specific data formats. It lets users run a set of geoprocessing tools, including some computing-intensive applications, in the distributed computing environment.

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

Online GIS Tools for UAVSAR Analysis

UAVSAR is a NASA project that uses a UAV equipped with the 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 a single image ranges from several hundred megabytes to several gigabytes. It also supplies prerendered images stored as KML or Keyhole Markup Zipped (KMZ) files, which can be visualized in Google Earth and Google Maps. The disadvantage of this file-based distribution system is that users must 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's difficult for general users to extract useful information for emergency response.

We 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 a WMS; Figure 2 shows several examples. We also provide WCSs that let users access the raw data in the interested study area at user-specified spatial resolutions. UAVSAR ground-projected products are roughly 6×6 meters in resolution, but users are often interested only in the partial image at a much lower spatial resolution, such as 30×30 meters. 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.

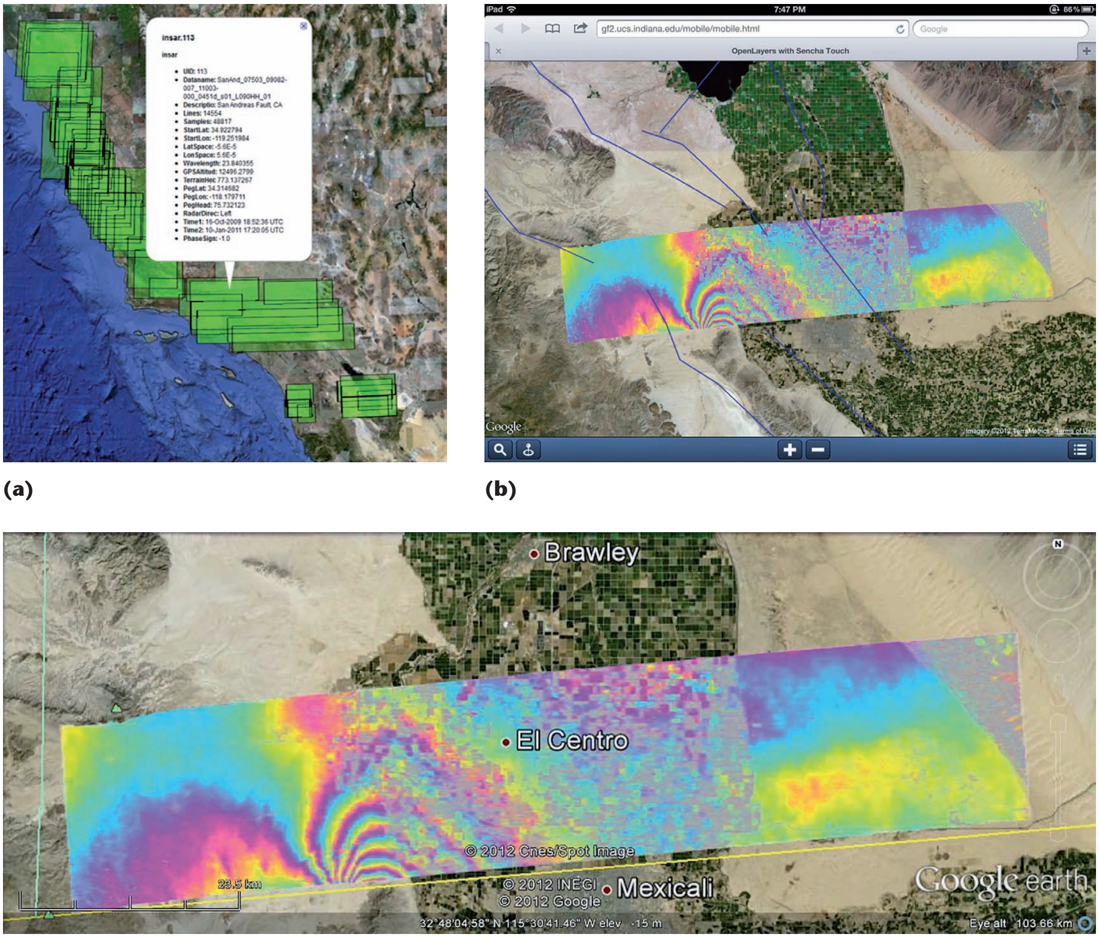
To support QuakeSim and E-Decider, we built several online tools that help general users analyze the UVASAR data directly through the Web browser. We use the LOS profile tool and the Simplex surface deformation inversion tool to demonstrate the structure of Web applications based on GIS services. These examples show how powerful yet complicated GIS capabilities can be when wrapped with simpler, application-specific APIs to build mashups and other third-party applications.

LOS Profile Tool

The LOS profile tool is used to calculate the cross-section of LOS 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 codeployed with GeoServer. The user interface (see Figure 3) is implemented on a separate server using Google Maps and JQuery JavaScript libraries.

In the first step, the user is shown a map with thumbnails of all available datasets. 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 let the user refine the selection by presenting a table with all available images that contain the selected point (right side of Figure 3a). 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 (Figure 3b), the user is shown 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 the LOS displacement and corresponding digital elevation model (DEM) data along the cross section. These values are extracted from 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



(a) (b) (c)

Figure 2. UAVSAR distribution example. (a) Image metadata, (b) image on mobile platform, and (c) Google Earth.

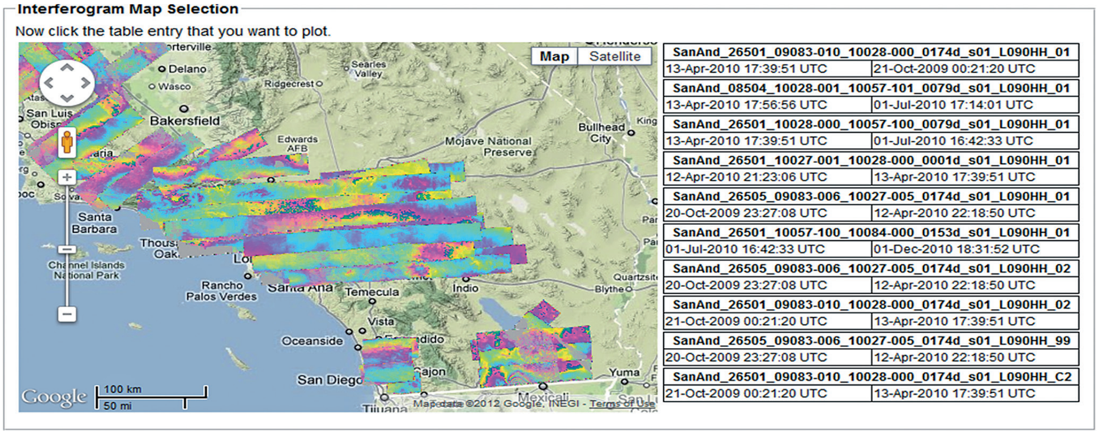
parameters including sampling methods and resolutions. Internally, the wrapper service queries two images at the same time: one for the LOS calculation and the other for DEM. It generates a series of locations along the cross section, with the spatial sampling resolution decided by the balance between the plot quality and the cross section's length. The profile tool service then calls the WMS `GetFeatureInfo` function for each location with the two images. The LOS is calculated based on the query results from one of the images.

Users can access the development preview of the LOS profile tool on the QuakeSim website (www.quakesim.org/tools/los-profile-plotter). Currently, 276 UAVSAR datasets are available, totaling approximately 1.5 Tbytes. It includes both standard products distributed through the 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 the moving average to be integrated.

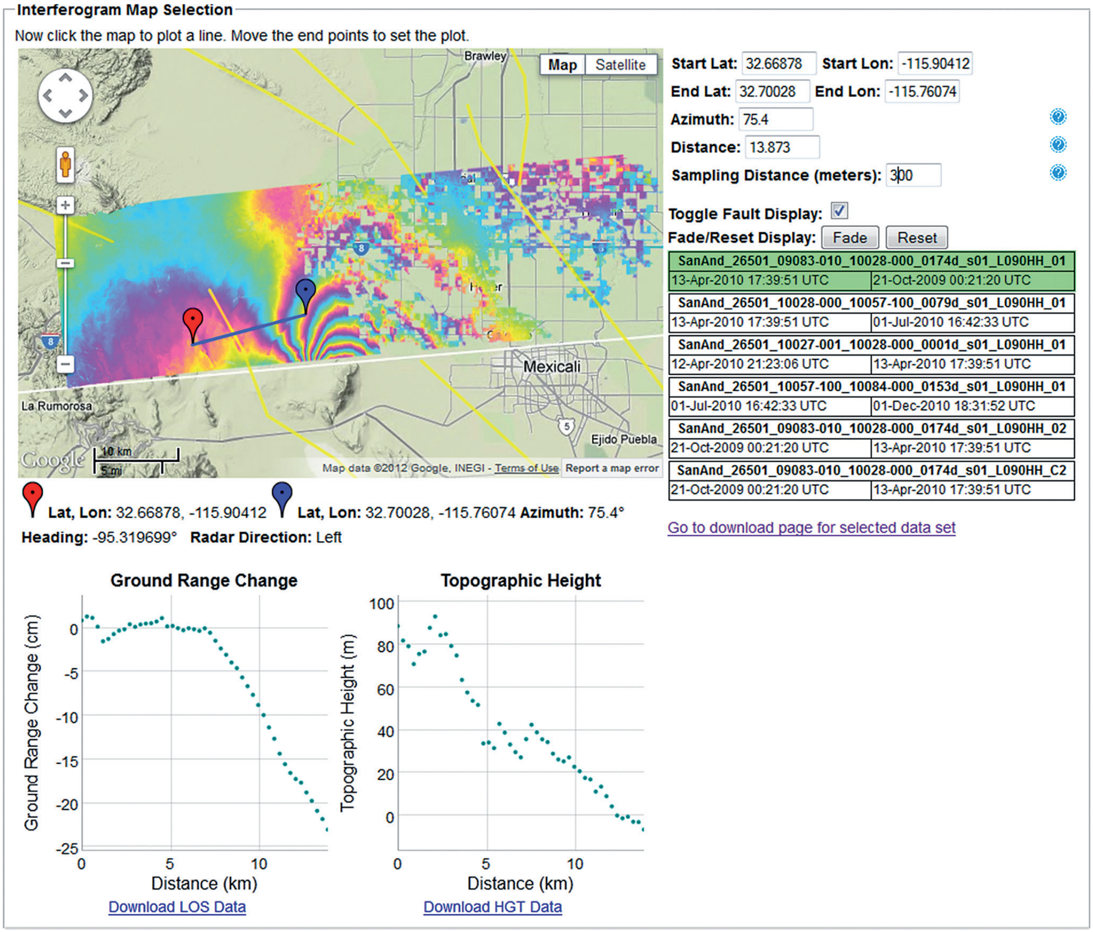
Simplex

Simplex is a command-line tool developed by collaborators at NASA JPL that optimally finds a dislocation model of a fault slip that accounts for observed GPS and InSAR deformation data. In this case, we need to provide a separately running Simplex service (not colocated with our GIS services) with a subset of the observational data in a target region. It's possible to transfer the entire image file or files, but this isn't optimal because Simplex is applied only to a subset of the data (such as the region of interest showing displacement fringe patterns associated with an earthquake).

Figure 4 shows the online Simplex tool's structure. The user examines the high-resolution interferogram image on Google Maps through the GeoServer WMS protocol. The polygon coordinates *n* of



(a)



(b)

Figure 3. Screenshot of the Line of Sight (LOS) profile tool. (a) Selection of images (step 1) and (b) LOS profile (step 2).

the user-selected region are sent as a 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 the GIS server and avoid downloading the data and running the Simplex tools on the local computing resource. The Simplex tool itself is also under continuous 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 service's standard output.

GIS Services for Emergency Response

The E-Decider project bridges the earthquake research and emergency response communities. The data products and tools from the 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 the QuakeSim project, along with remote sensing data, are accessible through Web service APIs.

One such service is the Hazus gadget (www.fema.gov/plan/prevent/hazus), which lets users generate scenario earthquakes for the US Federal Emergency Management Agency (FEMA) based on the forecasting results from QuakeSim. FEMA Hazus is a nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricanes in the US. Emergency planners identify the target region using information from the forecasted hot-spot areas, which are provided by the global forecast of future earthquake activity services from the Open Hazards Group (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 Open Seismic Hazard Analysis framework[8] (OpenSHA; www.opensha.org) to generate the Hazus input files for scenario earthquakes, which we can use for earthquake damage estimations. We can see the simulation results on Google Maps using the UAVSAR data to identify areas where the greatest deformation and damage has occurred and where emergency services should be focused. Figure 5 shows an example of the Hazus gadget.

Besides delivering both the products and Web services through the E-Decider portal, we investigated the integration of the service-based GIS system with the FEMA Unified Incident Command and Decision Support (UICDS; www.uicds.us) framework. UICDS is information-sharing middleware for the FEMA National Incident Management System's (NIMS's) incident management, which continuously receives and shares standardized data among many agencies during an incident.

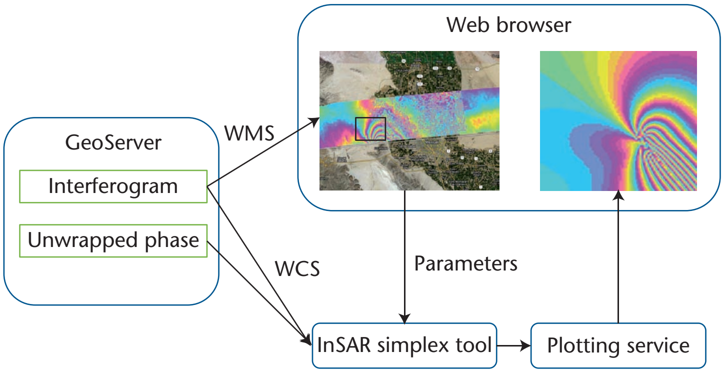


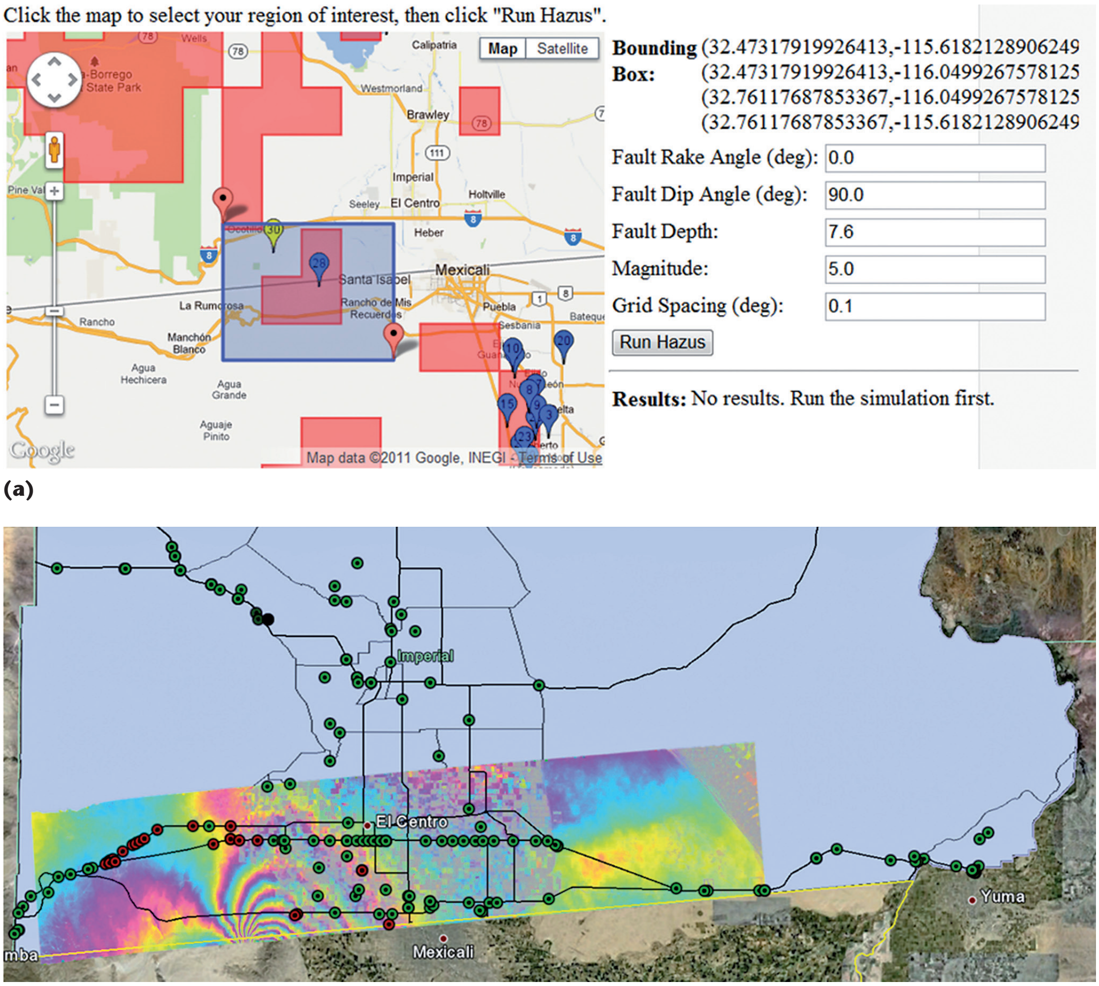
Figure 4. Structure of the Simplex tool. WMS serves as the high-resolution interferogram's online interface that lets the user select a research area (polygon). Data inside the research area are made available to the Simplex application through WCS. The plotting service generates the Keyhole Markup Language (KML), which contains the simulation result (Disloc interferogram).

Discussion

We've taken the first steps toward building the necessary infrastructure to support collaboration efforts for earthquake research and disaster response. Using service-based GIS technology, we built the platform for earthquake researchers to efficiently explore large amounts of data (particularly GeoTIFF-encoded SAR imagery). We've also given researchers the tools to deliver their knowledge in a timely manner to emergency planners and responders. However, many gaps remain for future research and development.

The computing resource, network bandwidth, and latency requirements of the QuakeSim and E-Decider tools as well as the data products needed after large earthquake events are uncertain. Developing countries have much less data—especially pre-earthquake data—compared to developed countries, as we've seen in the contrasting amount of data available from the Haiti 2010 and Japan 2011 earthquakes. The supporting computational infrastructure demands elasticity that goes beyond just starting up multiple VMs attached to large storage.

Cloud computing approaches provide a more advanced on-demand computing deployment solution.[9,10] Cloud computing provides elastically provisioned computing, software, and service



(a)

(b)

Figure 5. An example Hazus gadget. (a) The hot-spot forecast and fault model, and (b) a simulation result (red dots indicate damaged bridges).

infrastructures, typically implemented on a foundation of VM and virtual data storage technologies. Commercial offerings include the Amazon Web Services suite, Microsoft Azure, Rackspace, and Google App Engine. Open source software for building clouds include OpenStack (http://openstack.org), Eucalyptus (www.eucalyptus.com), Nimbus (www.nimbusproject.org), and OpenNebula (http://opennebula.org). Prominent cloud research efforts include NASA's Nebula and the National Science Foundation's FutureGrid. This elasticity lets users outsource their computing infrastructures, expanding or shrinking them as necessary.

Service-based GIS applications are based on open standards and aren't limited to the specific GIS packages and operating systems. They can be dynamically deployed as virtual appliances on top of advanced IT infrastructures; this makes computing clouds a natural fit for emergency response because the infrastructure usage levels are typically low 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 designed GIS servers as cloud-ready virtual appliances from the beginning. Future work includes developing additional cloud-specific features on the service-based GIS framework and migrating from the basic VM-hosting platform to the cloud infrastructure. Once an earthquake occurs, data providers can supply virtual images packed with essential data and software that can be deployed automatically or instantiated by emergency responders on a cloud.

Earthquake response involves a variety of institutes and agencies; it's inevitable that complex policy issues with regards to data security, sovereignty, 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). GeoServer 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's 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 or targets. Many such complex issues related to hybrid public and private clouds are yet to be explored.

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

Acknowledgments

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