Optimized Autonomous Space In-situ Sensor-Web for Volcano Monitoring

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Abstract—In response to NASA's announced requirement for Earth hazard monitoring sensor-web technology, a multidisciplinary team involving sensor-network experts (Washington State University), space scientists (JPL), and Earth scientists (USGS Cascade Volcano Observatory (CVO)), is developing a prototype dynamic and scaleable hazard monitoring sensor-web and applying it to volcano monitoring. The combined Optimized Autonomous Space - In-situ Sensor-web (OASIS) will have two-way communication capability between ground and space assets, use both space and ground data for optimal allocation of limited power and bandwidth resources on the ground, and use smart management of competing demands for limited space assets. It will also enable scalability and seamless infusion of future space and in-situ assets into the sensor-web. [1,2]

The prototype will be focused on volcano hazard monitoring at Mount St. Helens, which has been active since October 2004. The system is designed to be flexible and easily configurable for many other applications as well. The primary goals of the project are: 1) integrating complementary space (i.e., Earth Observing One (EO-1) satellite) and in-situ (ground-based) elements into an interactive, autonomous sensor-web; 2) advancing sensor-web power and communication resource management technology; and 3) enabling scalability for seamless infusion of future space and in-situ assets into the sensor-web. To meet these goals, we are developing: 1) a test-bed in-situ array with smart sensor nodes capable of making autonomous data acquisition decisions; 2) efficient self-organization algorithm of sensor-web topology to support efficient data communication and command control; 3) smart bandwidth allocation algorithms in which sensor nodes autonomously determine packet priorities based on mission needs and local bandwidth information in real-time; and 4) remote network management and reprogramming tools. The space and in-situ control components of the system will be integrated such that each element is capable of autonomously tasking the other. Sensor-web data acquisition and dissemination will be accomplished through the use of the Open Geospatial Consortium Sensorweb Enablement protocols. The three-year project will demonstrate end-to-end system performance with the in-situ test-bed at Mount St. Helens and NASA's EO-1 platform.

1. THE OASIS CONCEPT & PHILOSOPHY

OASIS responds to the NASA objective to "conduct a program of research and technology development to advance Earth observation from space, improve scientific understanding, and demonstrate new technologies with the potential to improve future operational systems". The OASIS concept focuses on using space-based, and in-situ sensors, working together in a semi-closed loop system that feeds information into a control system, which makes operation decisions "on-the-fly" (Figure 1). The OASIS research and development effort capitalizes on existing efforts in ground infrastructure enhancement and network development carried out at Mount St. Helens by USGS CVO.

The project has adopted the following design principles:

1. The OASIS design will leverage existing software/processes wherever possible.
2. The OASIS design will use commercial-off –the-shelf (COTS) components whenever possible.
3. The OASIS design will strive to be generic enough to be used with ground and space assets other than those slated in the prototype.

At the end of the project, OASIS will generate a "blueprint" for an integrated space – in-situ network for volcano hazard assessment, crisis response, and hazard mitigation.

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[1] 1-4244-1488-1/08/$25.00 ©2008 IEEE
[2] IEEEAC paper #1144, Version 2, Updated October 24, 2007

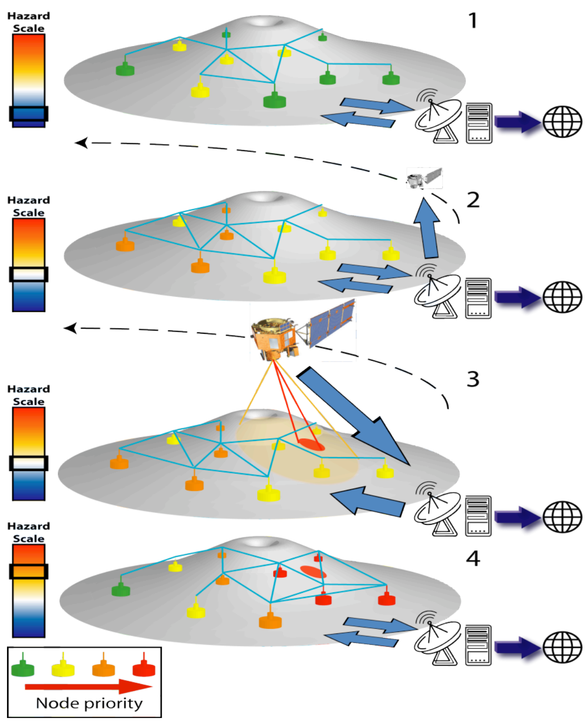


Figure 1: Optimized Autonomous Space - In-situ Sensor-web concept: 1. In-situ sensor-web autonomously determines topology node bandwidth and power allocation. 2. Activity level rises causing self-organization of in-situ network topology and a request for re-tasking of space assets. 3. High-resolution remote-sensing data is acquired and fed back to the control center. 4. In-situ sensor-web ingests remote sensing data and re-organizes accordingly. Data are publicly available at all stages.

2. BENEFITS TO EARTH SCIENCE

"Smart" ground sensor networks integrated with "smart" space-borne remote sensing assets would enable:

- Rapid response to track rapidly evolving science events.
- Resource allocations (e.g. bandwidth) dynamically to optimize in-situ data gathering.
- Automatic, rapid, re-tasking of scarce remote sensing assets to improve science return.

A key thrust of the OASIS development is to demonstrate how real-time remote-sensing information can effectively optimize resource allocation on the ground. In addition, OASIS' built-in scalability creates a test-bed for including future missions. The in-situ network will have the built-in capability to test the inclusion of future missions that measure, for example, temperature, gas emission, or deformation (InSAR).

Integrating in-situ assets with space assets has Earth science applications beyond volcanology. In-situ and remote sensing assets can be autonomously networked to track a wide range of science phenomena such as, regional or global flooding [4], tracking changes in glaciers [5] and polar cap ice changes [6], wild fires, and lake freeze/thaw. In all of these cases fixed "dumb" ground sensor data streams have been matched up with satellite data while OASIS will feed information back into a "smart" in-situ network.

At the end of 2009, a self-configuring, self-healing wireless sensor network will be deployed on Mount St. Helens and linked to the command and control of the Earth Observing One (EO-1) satellite. The ground sensor-web element will use observations data (seismic, infrasonic, ground deformation, and lightning detection) to trigger high-resolution data takes by EO-1. The data will be down-linked back to the ground sensor-web control center, where they will be ingested in a dynamic and scalable communication bandwidth allocation scheme to optimize communication and power usage. This test bed will be available for future ESTO and NASA earth science research.

3. SYSTEM COMPONENTS AND ARCHITECTURES

OASIS is a prototype system that will provide scientists and decision-makers with a tool composed of a "smart" ground sensor network integrated with "smart" space-borne remote sensing assets to enable prompt assessments of rapidly evolving geophysical events in a volcanic environment. The system will constantly acquire and analyze both geophysical and system operational data and make autonomous decisions and actions to optimize data collection based on scientific priorities and network capabilities. The data will also be made available to a science team for interactive analysis in real time. A typical science team is composed of a multidisciplinary group of vulcanologists that includes geodesists, remote sensing scientists, seismologists, geologists and gas geochemists.

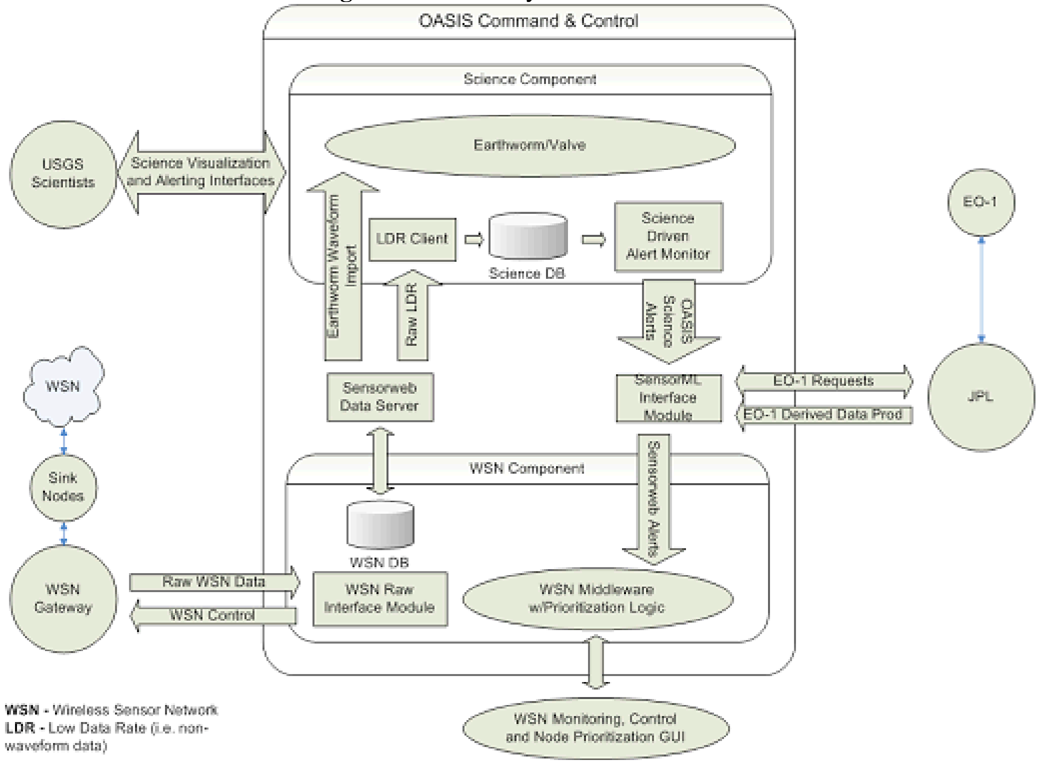
OASIS has the following components (Figure 2):

- OASIS Ground Segment (GS): This component consists of on-the-ground sensor nodes and all software modules for data acquisition, storage, analysis, communication, data flow, network operations as well as communication of data and requests between ground and space segments. It is basically a Wireless Sensor Network (WSN).

- OASIS Space Segment (SS): This component consists of JPL ground support SW, flight SW, and Earth Observing 1 (EO-1) satellite-borne sensors (and potentially other space assets such as ASTER, GOES, MODIS, INSAR).

- OASIS Command & Control: This component connects the ground and space segments and provides sensor web services to external users and components.

Figure 2: OASIS System Architecture



4. OASIS GROUND SEGMENT

An erupting volcano provides a challenging environment to examine and advance in-situ sensor-web technology. The crater at Mount St. Helens is a dynamic 3-dimensional communication environment, with batteries as the only reliable energy source. Various geophysical and geochemical sensors generate continuous high-fidelity data, whose priority depends on volcano status. There is a compelling need for real-time data, and sensors are destroyed occasionally by the eruption. Hence, an in-situ network must be self-configuring and self-healing, with a smart power and bandwidth management scheme, and autonomous in-network processing. The concept of an in-situ sensor-web is illustrated in Figure 3.

Topology management and routing. The in-situ sensor-web will be *self-organizing* and *self-healing*. It will respond to environmental changes (such as eruption progression), and will dynamically restructure the communication topology [7-12] so that other nodes are able to find an alternative energy-efficient path to reach the gateway in the event of node loss. In this way, at least partial networks survive and continuously forward data back to the gateway. To maximize both flexibility and efficiency, we will combine

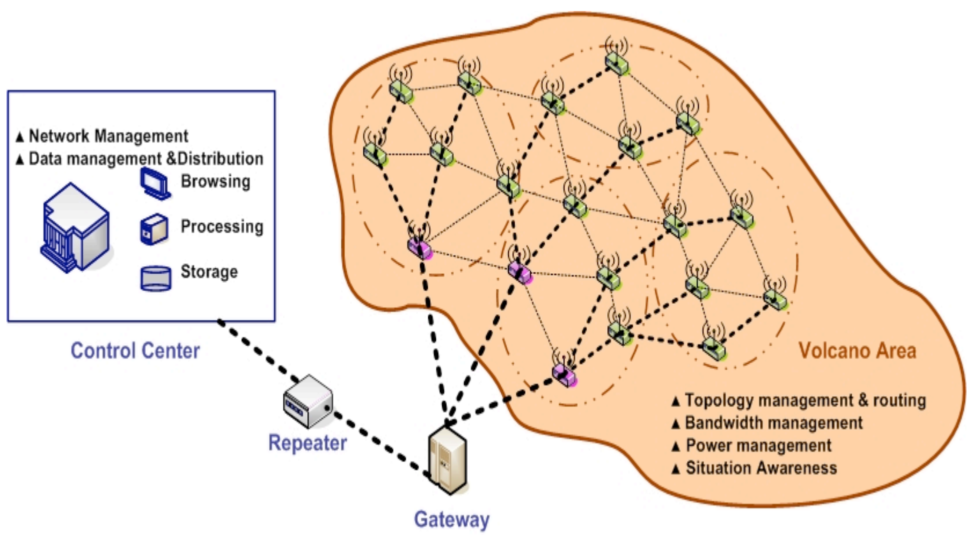


Figure 3: In-Situ Sensor Web architecture: 1. Sensor-nodes form logical clusters for network manage-ment and situation awareness; data flow forms a dynamic data diffusion tree rooted at gateway. 2. Smart bandwidth and power management according to environmental changes and mission needs. 3. Remote control center manages network and data, and interacts with space assets and Internet.

hierarchical logical control with flat routing topology. Hierarchical control architecture will be developed to enable scalable management, while routing can take advantage of all physical network connections to maximize efficiency.

A coordinator in each logical control cluster will be responsible for the network management and situation awareness. Unlike other hierarchical control architectures [27], the coordinator will not control routing in clusters. The routing algorithm will be developed based on all network connections, without being restricted by logical control cluster, making concurrent communication in a cluster possible. Normally the *data flow* follows a many-to-one routing paradigm, and form a data diffusion tree [12], with the gateway as a sink. In a data diffusion tree, each node periodically monitors its parent's status. If its parent dies, it broadcasts a join request and waits for other upper level nodes to accept it as a child. This idea also applies to integration of newly joining sensors, eliminating the need to reconfigure the network as it grows. The real-time reliable data dissemination protocols will be developed to support real-time command and control flows (e.g., network management and situation awareness) will be developed based on geocasting protocols.

Bandwidth management. In-situ volcano hazard monitoring networks provide an excellent test-bed for smart bandwidth management strategies. The limited bandwidth between gateway and sensor network constrains the high-fidelity operation and the real-time acquisition requirements.

OASIS will make use of the "many-to-one" network scenario by applying a time-optimal scheduling algorithm [13]. In this algorithm, each node locally calculates its duty cycle after the initial network deployment, and continuously adjust its schedule if the network topology changes. Every node either sends/receives messages or goes to sleep, which eliminates the energy waste of idle listening. Another advantage of this scheduling algorithm is the mitigation of interference between concurrent communication pairs. Consequently, both energy and communication efficiency are maximized. A GPS receiver at every node accommodates both synchronization and deformation measurements.
During active periods when bandwidth demands are highest, the network will prioritize the information flow in the network and reserve the bandwidth for high-priority data, based on mission-needs. For instance, if during volcanic activity, gas measurements are deemed highest priority, other data may be buffered to make more bandwidth available for gas data. Cluster coordinators will be able to automatically identify and select the minimum set of sensors that will provide mission critical data. Bayesian network techniques will be applied to address the sensor selection problem [14].
To further optimize bandwidth utilization, in-situ data reduction, compression and aggregation will be driven by science requirements. For example, when necessary, seismic data, typically recorded at 100Hz, will be reduced by two orders of magnitude at the node level by reporting an average Real-time Seismic Amplitude Monitor (RSAM) parameter, which is an established measurement of both earthquake and volcanic tremor [15]. In addition, continuous seismic data will be streamed into a buffer at each node, and when seismic events are triggered, the buffered waveform with precise time markers will be compressed and delivered to the control center for higher level processing.

Test-bed sensor node development. The staff of the USGS Cascades Volcano Observatory will design, prototype and test the data acquisition, sensors and communication hardware for the in situ sensor nodes. As part of this design process, early input from geodesists and seismologists will be incorporated to ensure appropriate sensors and capabilities are included. Use of commercial off-the-shelf (COTS) embedded microcontroller modules with high level programmability is planned to enable rapid development and application of an affordable platform. An expansion circuit and printed wiring board will be designed and produced that will include power conditioning and control, sensor input multiplexing, signal conditioning, signal digitization and communications interfaces. COTS sensors will include an L1 GPS receiver for timing and deformation monitoring, seismic accelerometer, microphone or microbarograph for infrasonic detection of explosions and emissions, lightning detector for ash cloud detection, and other sensors such as SO_2 gas, as deemed appropriate by scientific design criteria. Telemetry between nodes will be IEEE 802.15.4 and 900 MHz ISM spread spectrum as appropriate for the specific link requirements. In an active volcano, we can not rely on solar panel for energy because it will be covered by snow in winter and erupting ash in summer. In our hardware package design, each station consumes less than 2W power. With several Air-Alkaline batteries, our network is designed to survive for one year without solar panels.

5. OASIS SPACE SEGMENT

The OASIS will demonstrate the benefits of a feedback between ground and space operations. This capability is essential for two reasons:

- It will make for more efficient operation of the in-situ element
- It will trigger an in-situ deployment (or enhancement) at an unmonitored or poorly monitored volcano, and will be able to ingest input as it gradually appears on-line.

Just as the in-situ component requires a scalable architecture, the OASIS space element is designed to accommodate future space and in-situ observations as they come on-line. NASA's Earth Observing system already includes an array of sensors relevant to volcano monitoring (Table 1), each with its own data system and interfaces. In order to create a common interface to each of these heterogeneous systems, the OASIS will develop and implement the Open Geospatial Consortium Sensorweb

Enablement (SWE) services for space and in-situ sensors to task and acquire observation data.

Table 1 - Current and future volcano monitoring space assets		
Inst-rument	**Plat-form**	**Volcano-relevant measurement**
Hyperion	EO-1	High spatial and spectral resolution thermal emission
ASTER	Terra	High spatial resolution thermal emission
MODIS	Terra Aqua	High coverage, coarse resolution thermal emission
GOES	GOES	Coarse resolution, good coverage, near real-time thermal emission
AVHRR	POES	High resolution thermal emission
InSAR	Future	Deformation, surface change

OASIS will enhance the current EO-1 sensor-web architecture (see Figure 4.) by adding the capability of tasking a ground network behavior change, and creating alerts using the same mechanisms of ground alerts.

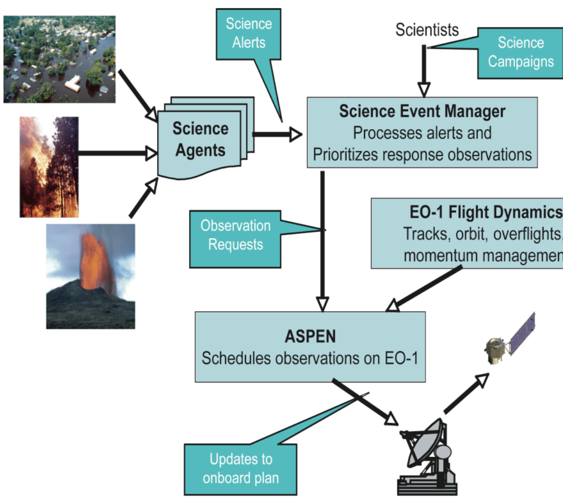


Figure 4: EO-1 sensor-web concept. The science event manager processes science event notifications and matches them with science campaigns, generating an observation request when a match occurs. The automated mission-planning system, ASPEN, processes these requests, integrating them with already scheduled observations according to priorities and mission constraints.

Feedback of EO-1 data into the in-situ element. A unique innovation of OASIS is feeding back information into the in-situ element. At present EO-1 triggering flow is ground-to-space, with the resulting remote sensing observations posted for scientific analysis. For example, the data generated by EO-1's Hyperion spectrometer (Figure 5) detects a region of thermal activity on Mount St Helens, but it is not altering the behavior of the ground networks. The high resolution and spatial coverage of Hyperion will feed information that cannot be obtained in-situ. Information such as "hot-spots" will be processed by the ground network control, which will re-prioritize bandwidth and power allocation.

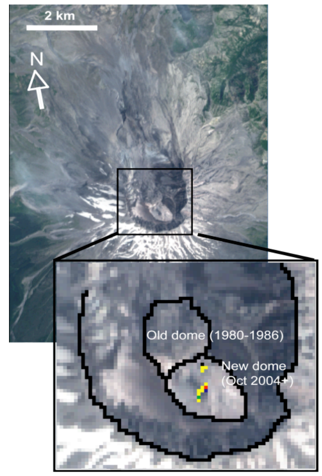


Figure 5: A high-resolution observation of Mount St. Helens' growing lava dome by EO-1's Hyperion in 2004. Pixel size is 30mX30m, significantly higher resolution than the in-situ node spacing. Pixel color indicates thermal radiation intensity.

Space observation data will also task a re-configuration of the in-situ network, adding a space-to-ground trigger channel.

6. OASIS COMMAND & CONTROL

Situation awareness and integration of in-situ and space observations. OASIS will incorporate existing real-time volcano monitoring and data-processing tools used by the USGS into the development of the command and control element. Using these tools the OASIS in-situ element will make real-time autonomous operational decisions according to local and remotely sensed environment changes. During active periods when demands on the nodes are highest, prioritization decision will be made by the command and control element. In periods of near quiescence, when volcanic activity is near or at background levels, cluster coordinators will be able to react to local changes (seismic, gas, deformation) without querying the control center.

In-situ network management. Network management components in both the sensor nodes and the control element will be designed with input from the end-user at all stages of the development. The network management algorithm will rely on scientific and engineering data for network topology and resource allocation decisions. However, a "manual" override of autonomous decisions by the monitoring entity will be built into the algorithm. For diagnostic purposes, engineering data will periodically be delivered to the control center to inform the system of an impending failure or to signal that a failure has occurred. Administrators will be able to examine performance on a holistic, network-wide scale. In addition, node-local fail-safes will provide a stable means of responding to node failures. Watchdogs [16] can reset or disable a node if regular operation is disrupted. Services, protocols, and applications will introduce watchdog checks, for validation and monitoring across the entire system. Fixed code segments and boot-loaders will enable remote reprogramming even if an application has failed.

Data ingestion and dissemination. OASIS will incorporate an information exchange system between space assets and other in-situ sensor webs anchored in OGC SWE web service interface. Unifying the OASIS data products, enables an immediate and uniform implementation of volcano hazard alerts a seamless inclusion of future space and in-situ assets. SWE web service interface provides the following:

1. The Sensor Planning Service (SPS): used to determine if a sensor observation request can be achieved, re-task the sensor to acquire science data, determine the status of an existing request, cancel a previous request, and obtain information about other OGC web services.
2. The Sensor Observation Service (SOS): used to retrieve observation data. This includes access to historical data as well as data requested and acquired from the SPS.
3. The Sensor Alert Service (SAS): used to publish and subscribe to alerts from the sensor.
4. A high level description of the sensors and their associated products and services using the Sensor Model Language (SensorML [44]). SensorML provides a high level description of sensors and observation processes using an XML schema methodology. It also provides the functionality for users[3] to discover the sensor on the web along with services to task and acquire sensor data.

The OASIS data management philosophy is to feed its data products into existing globally used data storage and analysis tools developed by the USGS. Over the last three years, the U.S. Geological Survey's Volcano Hazards Program has developed a suite of open-source software designed to manage and visualize volcano monitoring data. *VALVE* is a client/server system for serving, graphing and mapping nearly every type of data collected by a volcano observatory. The server side of *VALVE* answers requests for data, returning them in either graphical or numeric form. The client side of *VALVE* is a web-based application for efficiently interacting with the server. Internally, all data are stored in an SQL database, which provides high performance and reliability via freely available open-source software conforming to an established standard. The existing USGS software suite will be extended as needed to incorporate all of the data products created as part of this project and to serve such products to clients developed for EO-1 information exchange and re-tasking requests. This approach to accessing real-time volcano monitoring data promotes interoperability with data streams originating at all of the USGS domestic volcano observatories as well as international installations.

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[3] Users include humans as well as software agents acting as proxies for humans

7. Progress

OASIS has completed key milestones in its development. A thorough "System Requirements" phased has produced a first-of-a-kind "blueprint" for an integrated ground-space hazard monitoring network. A lab demonstration of the self-organization and self-healing mechanisms has been completed, and the ability to autonomously trigger EO-1 and to receive a feedback on the data request has been successfully tested. Using mainly commercial-of-the-shelf (COTS) components, sensor nodes have been constructed, and a first field test in a relevant environment is scheduled for the summer of 2008. OGC web services for EO-1 were completed, and work has begun on services for the ground component and a workflow for service coordination in response to alerts. The algorithms for OASIS data streaming into *VALVE* have been developed and implemented, including a new capability of generating *VALVE*-based alarms, which are key to the mutual triggering of the OASIS ground and space components. Work has begun on the OASIS command-and-control module and GUI.

An end-to-end system test in Mt. St. Helens in summer 2009. This test will consist of a verification of critical operational algorithms and assessment of system components performance of a sensor-web of 15-node in-situ nodes at Mount St. Helens and EO-1's Hyperion spectrometer. The sensor-web nodes will be packaged, powered and aerially deployed in a manner developed and proven effective during the ongoing activity of Mount St. Helens [17]. Data acquired by the sensor-web will be integrated into a *VALVE* server that can be accessed in real-time by scientists as well as autonomous clients that can communicate with the space-element of OASIS via an Internet connection at the control center.

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BIOGRAPHY

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Richard LaHusen, Senior Instrumentation Engineer at the USGS Cascades Volcano Observatory received his B.S from University of California, Davis and completed 4 years of graduate work at Humboldt State University then has worked as part of the USGS Volcano Hazards Team for the last 20 years. Throughout that period, he has developed instrumentation, telemetry systems and software for the research and monitoring of volcanic processes and hazards (Murray, et al, 1996). He developed the Acoustic Flow Monitor (AFM), an innovative system that incorporates in-situ analysis of seismic signals at remote nodes for the real-time detection and warning of volcanic debris flows that is in use around the world (LaHusen, 1996). He also developed a low-powered, high-resolution earth deformation monitoring system that optimizes allocation of limited resources for GPS data acquisition and communication needs (LaHusen and Reid, 2000). Most recently he introduced and applied aerial deployment of self-contained volcano monitoring instrumentation stations during the 2004-2005 eruption of Mount St. Helens (LaHusen, et al, 2006).

Sharon Kedar is a senior member of the technical staff in the Geodynamics and Space Geodesy group at the Jet Propulsion Laboratory, California Institute of Technology. His research areas include volcano seismology, volcano hazard mitigation, and GPS geodesy. He has extensively researched geysers and geothermal activity, and was a member of the 1997 USGS Mammoth Lakes volcano crisis monitoring team of the. He received his PhD in

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Behrooz A. Shirazi has been named the Huie-Rogers Chair Professor and Director of the School of Electrical Engineering and Computer Science. Shirazi comes to WSU from the University of Texas, Arlington, where he taught computer science and engineering since 1990 and was chair of the department for six years. Previous to his position at UTA, he was a faculty member at Southern Methodist University. His research interests are in the areas of pervasive computing, software tools, distributed real-time systems, scheduling and load balancing, and parallel and distributed systems. He has received grant support totaling more than $6 million dollars from federal agencies, including NSF, DARPA, and AFOSR, and private sources, including Texas Instruments and Mercury Computer Systems. He has received numerous teaching and research awards. He is currently the Editor-in-Chief for Special Issues for Pervasive and Mobile Computing Journal and has served on the editorial boards of the IEEE's Transactions on Computers and Journal of Parallel and Distributed Computing. He received his B.S. degree from Tehran Business College and his M.S. and Ph.D. degrees from the University of Oklahoma.

Ashley Davies is a volcanologist at the Jet Propulsion Laboratory-California Institute of Technology. He has a PhD in planetary science from Lancaster University, UK. He has extensively studied volcanoes on Earth and the jovian moon Io. He was a member of the NASA Galileo NIMS Team, is lead scientist on the NASA New Millennium Program Autonomous Sciencecraft Experiment (currently flying on Earth Observing-1) and is Principal Investigator of several NASA-funded research programs. He is the author of "Volcanism on Io: a comparison with Earth" recently published by Cambridge University Press. He was a recipient of the 2005 NASA Software of the Year Award for ASE.

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