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)), have developed a prototype of dynamic and scalable hazard monitoring sensor-web and applied it to volcano monitoring. The combined Optimized Autonomous Space - In-situ Sensor-web (OASIS) has two-way communication capability between ground and space assets, uses both space and ground data for optimal allocation of limited bandwidth resources on the ground, and uses smart management of competing demands for limited space assets. It also enables scalability and seamless infusion of future space and in-situ assets into the sensor-web. In this system, we developed: 1) a testbed 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) robustness and remote network management mechanisms. The space and in-situ control components of the system are integrated such that each element is capable of autonomously tasking the other. Sensor-web data acquisition and dissemination is accomplished through the use of the Open Geospatial Consortium Sensorweb Enablement protocols. The ground in-situ was deployed into the craters and around the flanks of Mount St. Helens in July 2009, and linked to the command and control of the Earth Observing One (EO-1) satellite.**[1]

I. INTRODUCTION

A multidisciplinary team involving sensor-network experts (Washington State University), space scientists (JPL), and Earth scientists (USGS Cascade Volcano Observatory (CVO)), have developed a prototype of dynamic and scalable hazard monitoring sensor-web and applied it to volcano monitoring (Figure 1). The combined Optimized Autonomous Space In-situ Sensor-web (OASIS) has two-way communication capability between ground and space assets, use both space and ground data for optimal allocation of limited bandwidth resources on the ground, and uses smart management of competing demands for limited space assets [1].

This research responds to the NASA objective [2] 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" (Table I of Summary of solicitation). OASIS stipulates the "Smart Sensing" topic area of this call, 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". OASIS has demonstrated this complete ground-space operation scenario (Figure 1) from the crater and flanks of Mount St. Helens. The OASIS research capitalizes on existing efforts in ground infrastructure enhancement and network development carried out at Mount St. Helens by USGS CVO.

II. BENEFITS TO EARTH SCIENCE

"Smart" ground sensor networks integrated with "smart" space-borne remote sensing assets can 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.

OASIS demonstrates how real-time remote-sensing information can effectively optimize resource allocation on the ground. In addition, OASIS's built-in scalability creates a test-bed for including future missions. The in-situ network has the built-in capability to test the inclusion of future missions that measure, for example, temperature, gas emission, or deformation.

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TABLE I
ESTO'S HAZMON OBJECTIVES AND OASIS' RESPONSE TO THEM

HazMon objective	OASIS' response
Foster and support inter-organizational cooperation	Involvement of the hazard monitoring agency (USGS Volcano Hazards Program) in all stages of system development making a two-way link between USGS in-situ resources and NASA remote sensing resources
Enable change to policy parameters in real-time	Integrate ground and space command and control
Management of flow of "value" among participating organizations	Optimization of usage of limited bandwidth resources on the ground and competing demands on limited space assets
Specify forward compatible interfaces in a manner that supports seamless transition from legacy resources to next generation resource deployment	Use SensorML for internal data ingestion and external data dissemination, and pipe data products to commonly used USGS data management system, VALVE
Optimization of usage of the HazMon system in an event of competing multiple Hazards	Generic system design and data management strategy to enable infusion of future ground and space assets
Value management and fair allocation of resources between participating organization	Integrate ground and space command and control, and optimize usage of limited bandwidth resources on the ground and competing demands on limited space assets

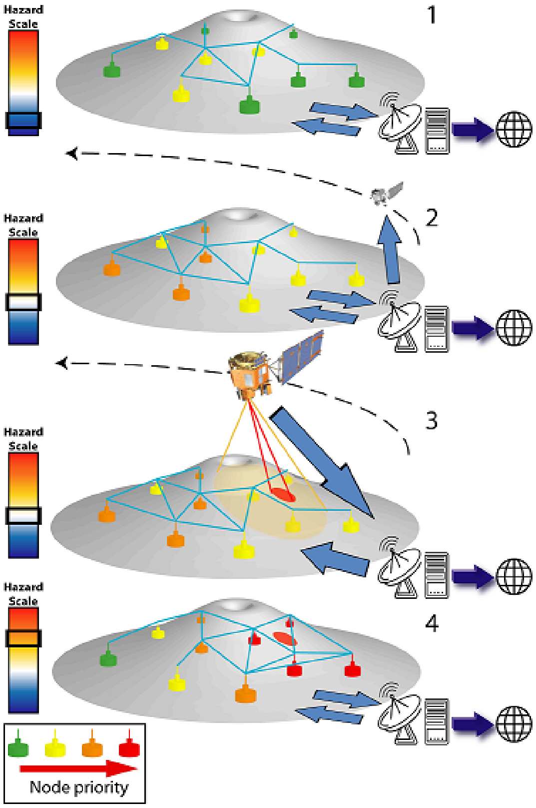

Fig. 1. Optimized Autonomous Space - In-situ Sensor-web concept: 1. In-situ sensor-web autonomously determines bandwidth allocation of the ground in-situ. 2. Activity level rises causing self-organization of in-situ network topology and a request for re-tasking of space assets. 3. High-resolution remote-sensing 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.

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 [3] [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. In OASIS, a self-configuring and self-healing wireless sensor network is linked to the command and control of the Earth Observing One (EO-1) satellite. The ground sensor-web element uses observations data (seismic, gas, and ground deformation) to trigger high-resolution data takes by EO-1. The data is down-linked back to the ground sensor-web control center, where they are ingested in a dynamic and scalable communication bandwidth allocation scheme to optimize communication usage. This test bed is available for future ESTO and NASA earth science research.

This scenario addresses the goals set in ESTO's study on Hazard Monitoring (HazMon). HazMon identifies the need to integrate multiple arrays of sensors from vantage points varying from the ground to space into a unified sensor-web, in order to provide timely streaming of information to decision makers [7]. It describes a "system-of-systems" approach that provides an architectural context for coordination of resources, which are traditionally scattered among disciplines and agencies. The HazMon study lists key objectives for meeting ESTO's future sensor-web needs. Table I summarizes those objectives and how OASIS research addressed them.

III. SYSTEM COMPONENTS AND ARCHITECTURES

OASIS is a prototype system that provides 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 constantly acquires and analyzes both geophysical and system operational data and makes autonomous decisions and actions to optimize data collection based on scientific priorities and network capabilities. The data is also available to a science team for interactive analysis in real time. A typical science team is composed of a multidisciplinary group of volcanologists that includes geodesists, remote sensing scientists, seismologists, geologists and gas geochemists.

OASIS has the following components shown in Figure 2.

- OASIS Ground Segment (GS): This component consists of on-the-ground sensor nodes and all software modules

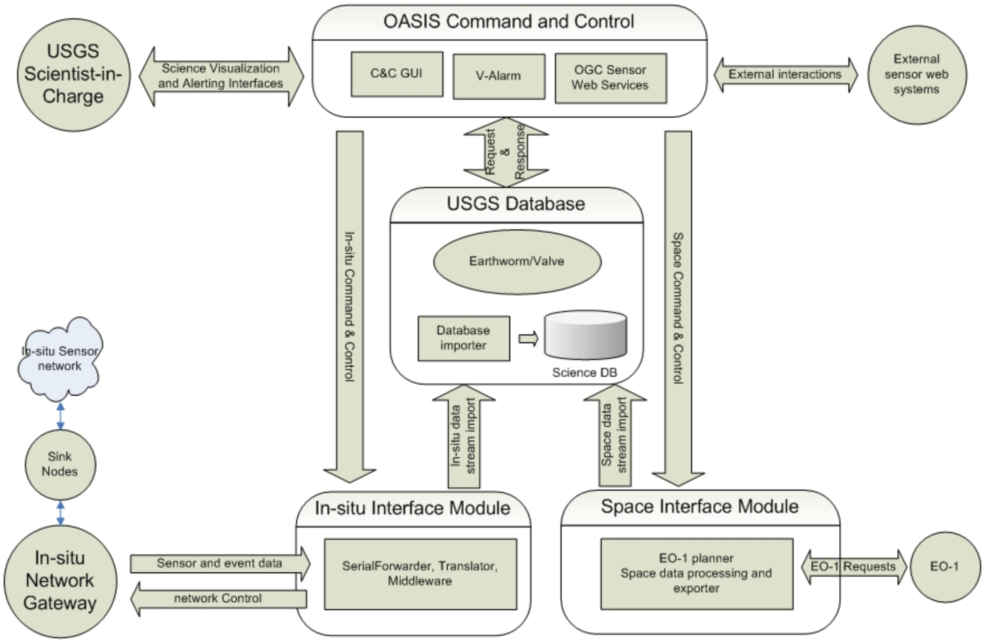

Fig. 2. OASIS System Architecture

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 software, flight software, 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.

IV. 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. The network shall deliver as much raw data as possible and give more yield to the data of higher priority. Additionally, the event data (with the highest priority) shall be delivered without data loss. Stations can be destroyed occasionally by the eruption. Hence, an in-situ network must be self-configuring and self-healing. The network also needs to be remotely manageable so that after deployment, users may adjust system parameters, such as sampling rate, data priority, and RF channel.

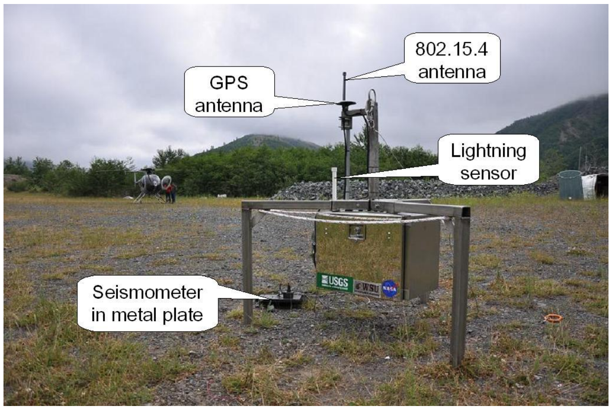

Fig. 3. Spider sensor node is equipped with a seismometer to detect earthquakes, a GPS receiver to pinpoint the exact location and measure subtle ground deformation, an infrasonic sensor to detect volcanic explosions, and a lightning sensor.

A. *Hardware Development*

The staff of the USGS Cascades Volcano Observatory has designed 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 is incorporated to ensure appropriate sensors and capabilities are included. Commercial off-the-shelf (COTS) embedded microcontroller modules with high level programmability are used to enable rapid development and application of an affordable platform. An expansion circuit and printed wiring board was designed and supported power conditioning and control, sensor input multiplexing, signal conditioning, signal digitization and communications interfaces. COTS sensors include an L1 GPS receiver for timing and deformation monitoring, seismic accelerometer, microphone or microbarograph for infrasonic detection of explosions and emissions, and lightning detector for ash cloud detection. Telemetry between nodes uses IEEE 802.15.4 ISM spread spectrum. In an active volcano, we cannot rely on solar panels 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.

B. Software Development

Most of the sensor network research to date has focused on performance but not long term viability. The ground network software designed by WSU has thoroughly considered both performance and robustness. We designed automatic fault detection and recovery mechanisms, which automatically rolls the system back to the initial state if exceptions occur. To enable remote management, we designed a configurable sensing and flexible remote command and control mechanism with the support of a reliable dissemination protocol. To maximize data quality, we designed event detection algorithms to automatically detect volcanic events and prioritize the data, and designed adaptive data transmission protocols to ensure higher priority data with higher delivery ratio. The raw data is compressed with a light-weight compression algorithm to reduce bandwidth demands.

Quality-driven data collection. The USGS scientists expect the network to deliver as much raw data as possible and give higher data yield to data of high priority (e.g. event data). For such a high data rate application, a key challenge is how to collect the high-fidelity data subject to the limited bandwidth available to sensor nodes. Adaptive data transmission protocols were designed to ensure higher priority data with higher delivery ratio.

The seismic event data is the most critical for volcano studies, and USGS scientists require reliable delivery of the data with the highest priority. We used the STA/LTA (short-term average over long-term average) algorithm [8], [9] to detect seismic events. The STA/LTA algorithm is based on RSAM (Realtime Seismic Amplitude Measurement), which is calculated on raw seismic data samples every second. Once a seismic event is detected, the event data is assigned the highest priority and reliably delivered to the gateway by a reliable data transfer protocol.

Non-event data is also desired by USGS scientists. However, the sensor data is not equally important; thus, we need to treat the data accordingly and control the Quality of Service (QoS). We designed a Tiny-Dynamic Weighted Fair Queuing algorithm (Tiny-DWFQ [10]) to assign proper QoS for each packet based on the data priorities and network situations. Once the QoS is assigned, Tiny-DWFQ ensures that the packets are sent throughout the network in a way that guarantees that the desired QoS requirements are upheld.

To reduce the bandwidth demands and maximize the data return over the unreliable and low rate radio links, an Adaptive Linear Filtering Compression (ALFC) [11] algorithm was designed to compress the seismic raw data. It is a lightweight compression algorithm tailored for sensor networks with code size of only 768 bytes. Considering the relatively modest computational power of existing sensor platforms, ALFC does not use floating-point operations and has very low computation and energy cost. Our method relies on adaptive prediction, which eliminates the need to determine prediction coefficients a priori and, more importantly, allows the compressor to dynamically adjust to a changing source.

Controlling access to the channel, generally known as MAC protocol, plays a key role in determining channel capacity utilization. To provide high channel capacity utilization with low congestion, we developed a new TDMA MAC protocol called TreeMAC [12] to regulate the channel access. The design of TreeMAC is based on the key observation of multi-hop data collection networks that the bandwidth allocation of any node shall be no less than that of its subtree, so that the nodes closer to the sink have enough bandwidth to forward data packets for the nodes that are further away. With TreeMAC the network can achieve a data throughput to the gateway of at least 1/3 of the optimum assuming reliable links.

Robustness and remote network management. All of our nodes are in rugged terrain and only reachable by helicopter. The field maintenance is difficult, if not impossible. Thus, software dependability and reliability is a major concern. Nasty bugs may occur after deployments [13]. To survive unforeseen software faults, our sensor node automatically detects and self-recovers from software failures. We exploited the benefits of watchdog. The iMote2's hardware watchdog can restart the node under exceptions such as dead loop, memory errors, and stack overflow. In addition, software failures also can be caused by unexpected logic errors. We further developed a software watchdog to enable self-recovery from erroneous states. To reduce the reboot cost to the minimum, important parameters and states are written to Flash when configured by remote users, and are restored once a node reboots.

Considering the longevity and remoteness of environmental monitoring, online reconfiguration of the network and motes is highly desired for system deployments. Thus, we developed a comprehensive remote network management mechanism that provides interactions between the users and the network in the field. The remote command and control [14] is based on a flexible Remote Procedure Call (RPC) mechanism [15]. It allows a PC to access the exported functions and any global variables of a statically-compiled program on sensor nodes at run time. To ensure the reliable dissemination of RPC messages over multi-hop paths, we have designed a reliable data dissemination protocol *Cascades* [16]. The RPC mechanism gives users great flexibility to read/write system variables and run any exported functions. The OASIS stations are designed to be smart and flexible with the sensing parameters adjustable based on environmental conditions and mission needs. Our sensor driver performs synchronized sampling operation and maintains sensing parameters, such as sampling rate, ADC channel, and data priority. All these parameters could be tuned according to environmental and resource situations to conserve energy or increase fidelity via RPC commands.

The *Cascades* protocol ensures 100% reliable dissemination of the command messages by utilizing the parent-children relationship in a data collection tree: each node monitors whether its children have received the broadcast messages through snooping. Each node rebroadcasts periodically until successful reception is confirmed by all children. The broadcast flow does not depend on the data collection tree structure. A snooped new message from neighbor nodes will be accepted and rebroadcasted. Therefore, it is possible that a node first hears new data from its children, before it hears it from its parent. In other words, it is a fast opportunistic data dissemination protocol. In addition, *Cascades* performs a reactive fetch mechanism if there is gap in packet sequence, which denotes missing packets.

After we deploy a sensor network into a remote environment for long-term monitoring, the network functionality may need improvement or fix for software failures. Thus, it is important to support remote software upgrades. Deluge is the de facto network reprogramming protocol that provides an efficient method for disseminating a program binary over the wireless network and having each node program themselves with the new image. We ported Deluge to the iMote2 platform, and used it for remote software upgrade.

V. OASIS SPACE SEGMENT

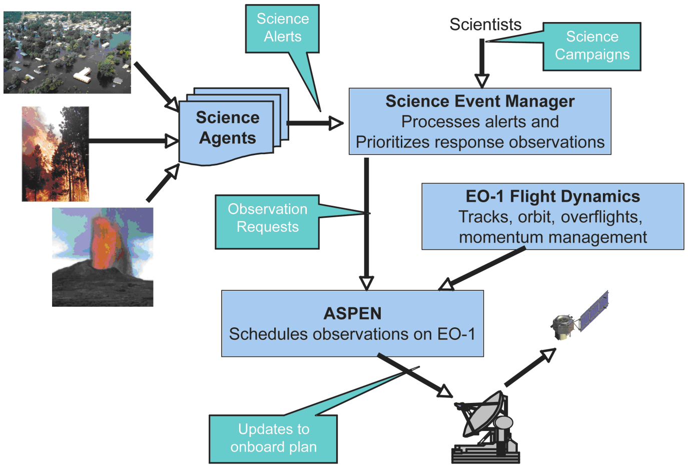

Fig. 4. EO-1 sensor-web concept. The science event manager processes science event notifications and matches them with science campaigns, generating an observation request when a match occurs. The automated mission-planning system, ASPEN, processes these requests, integrating them with already scheduled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

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

- It makes for more efficient operation of the in-situ element.
- It can trigger an in-situ deployment (or enhancement) at an unmonitored or poorly monitored volcano, minimizing resources required for constant monitoring.
- Feedback from in-situ provides valuable planning information on highly constrained remote sensor operations.
- Coordination between space and ground provides valuable temporally coincident data for science analysis.

NASA's Earth Observing system already includes an array of sensors relevant to volcano monitoring (Table II), each with its own data system and interfaces. Open Geospatial Consortium Sensor Web Enablement (SWE) services for space and in-situ sensors to task and acquire observation data in OASIS were adopted and developed to serve as a baseline for interoperability between sensors integrated in the future.

OASIS has enhanced the current EO-1 sensor-web architecture [17] by adding the capability of tasking a ground network through alert services (SAS) and automated push of high level data analysis results to time-series evaluation tools (see VALARM in Command & Control) that can be used to task space assets. Both the ground-to-space and space-to-ground triggers and responses are autonomous but not real-time due to intermittent communications with the EO-1 spacecraft (typically 6 contacts per day). While these triggers are limited by the challenges of registration of EO-1 imagery and moderate temporal resolution of EO-1 (10 overflights per 15 days) they do demonstrate the feasibility and utilities of integrated space ground sensing. Further details of the timeline of ground to space triggering are described in [18].

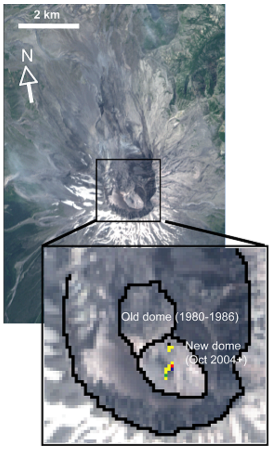

Fig. 5. A high-resolution observation of Mount St. Helens's growing lava dome by EO-1's Hyperion in 2004. Pixel size is 30mX30m, significantly higher resolution than the in-situ node spacing. Figure courtesy [17].

Feedback of EO-1 data into the in-situ element. A unique innovation of OASIS is feeding back information into the in-situ element. High spatial resolution data generated by EO-1's Hyperion spectrometer (Figure 5) [17] is fed through a thermal analysis element to detect a region of thermal activity on the target area (e.g. Mount St Helens), analyzes the data, and pushes results to the ground segment where it is ingested for anomalous characteristics (e.g. exceeding running average thermal output) that can be used for triggering change of behavior. Information such as geolocation of "hot-spots" is processed by the command and control, which will re-prioritize bandwidth allocation.

VI. OASIS COMMAND & CONTROL

Situation awareness and integration of in-situ and space observations. We have incorporated existing real-time volcano monitoring and data-processing tools used by the USGS into the development of the command and control element, and delivered some valuable additions to the suite, including VALARM which is a real-time data analysis and triggering

TABLE II
CURRENT AND FUTURE VOLCANO MONITORING SPACE ASSETS

Inst-rument	Platform	Volcano-relevant measurement	OASIS Integrated
Hyperion	EO-1	High spatial and spectral resolution thermal emission	Yes
ASTER	Terra	High spatial resolution thermal emission	No
MODIS	Terra Aqua	High coverage, coarse resolution thermal emission	No
GOES	GOES	Coarse resolution, good coverage, near real-time thermal emission	No
AVHRR	POES	High resolution thermal emission	No
InSAR	Future	Deformation, surface change	No

software module. Using these tools the OASIS in-situ element makes real-time autonomous operational decisions according to local and remotely sensed environment changes. During active periods when demands on the nodes are highest, prioritization of data is made by the command and control element, following rules prescribed by a domain expert. In periods of near quiescence, when volcanic activity is near or at background levels, cluster coordinators are able to react to local changes (seismic, gas, deformation) without querying the control center.

In-situ network management. Network management algorithms rely on scientific and engineering data for network topology and resource allocation decisions. For diagnostic, management, and self-feedback purposes, engineering data is delivered from sensor nodes and collected at the control center to inform the system of weak network links, low power readings, data throughput, and risk of an impending or notice of a current failure. All of this telemetry is accessible to the real-time analysis and triggering software VALARM and self reconfiguration. However, the command and control center also provides a "manual" override of autonomous decisions by the end-user/domain expert. Network management components in the control element have been designed with input from the end-user (USGS domain experts) at all stages of the development. Administrators are able to examine performance on a holistic, network-wide scale, respond through manual intervention of network operating states, and make amendments to autonomy-rules.

Data ingestion and dissemination. OASIS incorporates an information exchange system between space assets and other in-situ sensor webs anchored in OGC SWE web service interface, relying heavily on Sensor Alert Services for interoperation. By unifying the OASIS data products, we enable 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 (Space Segment only).
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 sensors.

The OASIS data management philosophy is to feed its data products into existing globally used data storage and analysis tools developed by USGS. VALVE is a client/server system for serving, graphing and mapping nearly every type of data collected by a volcano observatory. 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. VALARM is a piece of software developed by OASIS to interoperate with VALVE data and the SQL database, allowing users to configure real-time analysis and attach alerting mechanisms to analysis triggers, including but not limited to generating SAS alerts delivered via HTTP, opening TCP/IP sockets to push XSL transformed data payloads, and communicating with SMTP to deliver emails or cell phone text messages. VALVE also provides the foundation for the ground segment's SOS, allowing OGC clients to query and subset the historical data collected from in-situ sensors.

VII. FIELD DEPLOYMENT

Two field deployments of the in-situ ground sensor network have been conducted on Mount St. Helens. The first one was a trial deployment [19] in October 2008 that air-dropped a sensor network prototype with basic functionalities onto the crater to explore the system requirements and environmental constraints in the rugged terrains. The success of the deployment alleviated the doubts of domain scientists and proved to them that a low-cost sensor network system can support real-time monitoring in extremely harsh environments. With the lessons from that deployment, we improved the system design significantly and conducted another deployment in July 2009 with a larger scale sensor network of 15 OASIS stations (see Figure 7) providing a much wider spatial coverage.

The deployed in-situ sensor network is comprised of two branches. Each branch operates with a separate data collection sink and radio channel. The first branch network (nodes $0 - 6$) is mostly placed inside the crater. The second branch network (nodes $7 - 14$) is deployed around the flank forming a semicircle. Some OASIS stations co-locate with existing USGS stations including VALT, SEP, and NED, which serve as ground truth to evaluate the data quality of OASIS stations.

Figure 6 illustrates the end-to-end configuration of OASIS system. The ground network delivered real-time volcanic signals to the sink nodes through multi-hop relays. The gateway relayed the data stream to WSUV through a microwave link of 50 miles. In the lab, a customized TinyOS tool SerialForwarder

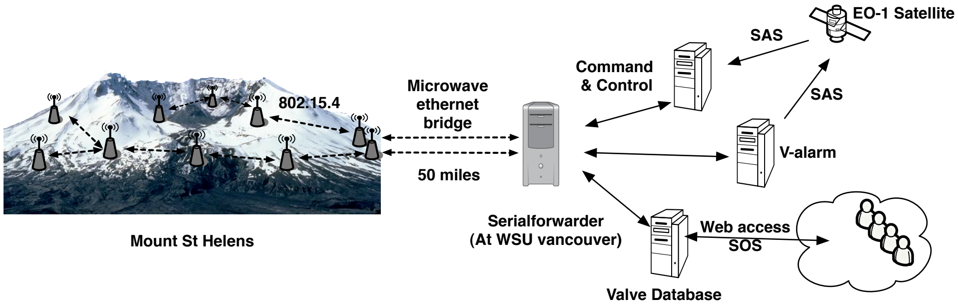

Fig. 6. The In-Situ Sensor-Web configuration.

Fig. 7. Field deployment map

forwards the data between the sensor network and the Internet. Multiple control clients may connect to it, access the sensor data stream, and control the network in real time. The data stream from seismic, infrasonic, lightning sensors, and GPS, as well as RSAM, battery voltage and LQI (Link Quality Indicator) data, are logged into VALVE database for permanent storage. V-alarm (volcano activity alarm) can automatically identify earthquake events from the raw data stream. Once an event is triggered, V-alarm can send event alerts via email or text messages to the corresponding scientists in charge. The Command & Control center is for situation awareness and integration of in-situ sensor network and space observations from EO-1 satellite. It incorporates existing real-time volcano monitoring and data-processing tools used by the USGS and makes real-time autonomous operational decisions to control the sensor network. The data acquired by the ground network are streamed to UGGS VALVE database and processed by science analysis tools in real-time.

VIII. SYSTEM EVALUATION

We rigorously evaluated the system from aspects including data quality, event detection, and autonomous feedback between space segment and the ground in-situ.

Data Quality. One important aspect of evaluating a data collection system is the data quality. To assess the quality of our data we compared OASIS node 1 with the co-located broadband station VALT BHZ. Due to difference in ADC resolution, we scaled the data samples before comparison. Figure 8 shows 50-minute seismic data from OASIS node 6, node 1, and VALT station during the time period from GMT 07/20/2009 18:20 to GMT 07/20/2009 19:10. We can see that the deviation of the noises from OASIS node 1 is only $0 \sim 17$ while the noise level of VALT is in the range of $0 \sim 16$. We can see that the OASIS station with Geophone seismic sensor can achieve similar data quality. It is worth mentioning that the seismic sensor of the broadband station costs about $\$10,000$ ($\$25,000$ for the whole station), while the OASIS station is smarter and only costs about $3000.

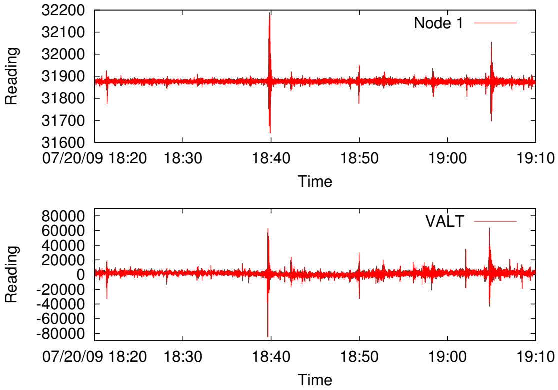

Fig. 8. The seismic waveform of OASIS node 1, and VALT.

Event Detection. When our STA/LTA algorithm identifies seismic events, it assigns the highest priority 7 to the seismic signals, as shown in Figure 9 (Middle). Those data are reliably delivered to the gateway with the underlying adaptive transmission protocols. Figure 9 (Bottom) shows the energy distribution over the frequency spectrum.

Space-to-ground Triggering. Figure 10 shows the space-to-ground triggering and the prioritized data delivery mechanism in the ground network. For example, as snow accumulates in the Mount St. Helens, OASIS node 4 was buried into snow incrementally. During that process, the data stream of node 4 experienced more and more packet loss. However, once the data priority was raised to highest level due to space triggering, the data during that period were reliably delivered.

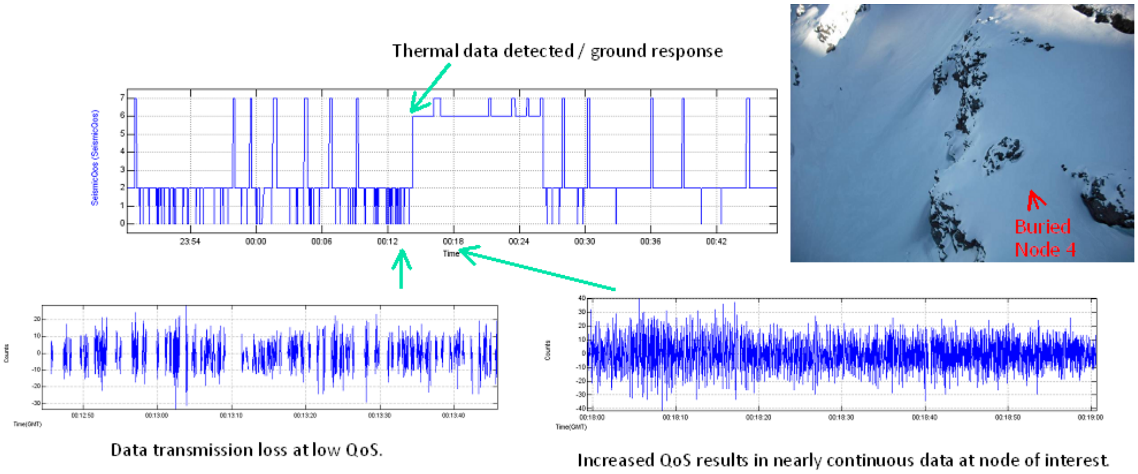

Fig. 10. Space-to-ground triggering raised the data priority to the highest level, resulting in reliable delivery of the data stream from node 4 .

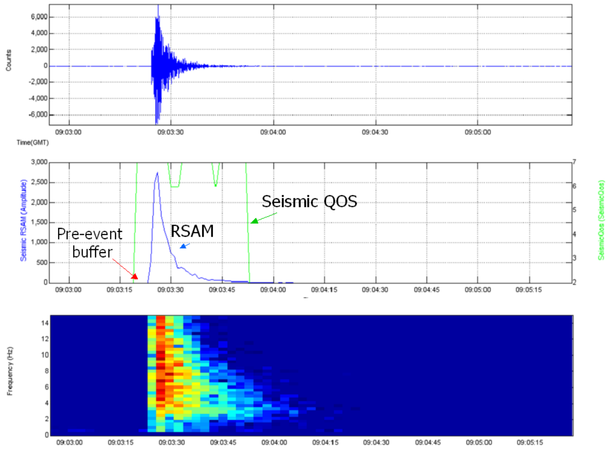

Fig. 9. Event detection and prioritization. (Top) Seismic raw data. (Middle) Data priority is raised to 7 when an event is detected. (Bottom) The energy distribution over the spectrum; red color reflects strong energy.

IX. CONCLUSIONS

The OASIS system has been designed, tested, and deployed on Mount St. Helens. The ground in-situ and the space element are well integrated forming an autonomous system that efficiently monitors the volcanic activities on Mount St. Helens.

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