A Multi-agent Space, In-situ Volcano Sensorweb

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Abstract

We have deployed and demonstrated operations of an integrated space in-situ sensorweb for monitoring volcanic activity. This sensorweb includes a network of ground sensors deployed to the Mount Saint Helens volcano as well as the Earth Observing One spacecraft. The ground operations and space operations are interlinked in that ground-based intelligent event detections can cause the space segment to acquire additional data via observation requests and space-based data acquisitions (thermal imagery) can trigger reconfigurations of the ground network to allocate increased bandwidth to areas of the network best situated to observe the activity. The space-based operations are enabled by an automated mission planning and tasking capability which utilizes several Open Geospatial Consortium (OGC) Sensorweb Enablement (SWE) standards which enable acquiring data, alerts, and tasking using web services. The ground-based segment also supports similar protocols to enable seamless tasking and data delivery. The space-based segment also supports onboard development of data products (thermal summary images indicating areas of activity, quicklook context images, and thermal activity alerts). These onboard developed products have reduced data volume (compared to the complete images) which enables them to be transmitted to the ground more rapidly in engineering channels.·

1 Introduction

Sensorwebs offer the potential to enhance measurement and study of dynamic phenomena. Volcanoes in particular can benefit from the integration of a wide range of sensors and modalities. Scientists are modeling volcanoes using extremely sensitive instruments that can detect magma moving at depths kilometers beneath the surface of the Earth, detect subtle inflations of the ground, and thermal signatures from fresh magma (either from ground or space-based sensors). In particular, ground and space based sensing of volcanos are extremely complementary in that ground-based sensors can provide highly detailed information from a single physical location and space based sensing can provide data over large areas with a single overflight.

This paper reports on recent developments to integrate space based remote sensing using the Earth Observing One spacecraft with an intelligent network of "spider" instrument deployed to the surface of the Mount Saint Helens volcano. This work extends a previously existing space-based sensorweb that utilized data from MODIS (on the Terra and Aqua spacecraft), GOES, Earth Observing One and ASTER (on Terra) instrumentation and linked in with hybrid manual reporting systems such as the Volcanic Ash Advisory Centers (VAAC) and Air Force Weather Advisory System (AFWA).

We begin by outlining our general agent-based architecture to sensor integration, highlighting the fractal nature of sensorwebs. We then cover the prior EO-1 centric space based sensorweb. Next, we describe the Mount Saint Helens in-situ network that was recently deployed. We then describe the ground to space and space to ground triggerings. Finally, we discuss the status of the network and plans for future work.

2 A General Agent-based Sensorweb Framework

We have deployed a general agent-based framework for sensorwebs focused on the EO-1 spacecraft. In this architecture, the principal sensorweb processes of event detection, campaign matching, and response generation are performed continuously. This cycle is shown below in Figure 1. For example, the MODVOLC system processes MODIS instrument data from the Terra and Aqua spacecraft that cover every spot on the Earth at least four times per day (two daylight and two night). This instrument data is processed using the MODVOLC algorithms [Wright et al. 2003, 2004] producing a set of event records indicating the time, location, and magnitude of the thermal detections. Therefore the MODVOLC system can be viewed as a processing agent that monitors MODIS data and produces thermal event notices (for consumption by other agents). These event alerts are processed at JPL by the campaign manager. The campaign manager cross matches the events against scientist defined campaigns where a campaign represents a rule going from a set of events to a trigger action/request to request further observations, acquire more data, or reconfigure a sensorweb. Logically speaking a campaign is a logical expression of event notices (and can refer to timing, magnitude, or frequency of event) and if the conditions are met it causes a series of requests as defined by the scientists. For example, a campaign might state that if two MODVOLC thermal alerts occur on the target "Mount Saint Helens" in a 24 hour period request an observation from EO-1 Hyperion and ASTER if they occur in the next 48 hours.

Requests for reconfiguration, observations, and data are sent to the appropriate agent controlling the requested asset. In the example above, requests would be sent to the ASTER and EO-1 agent. The EO-1 agent uses the ASPEN planning system to evaluate requests. Based on the priority of the incoming requests and the existing EO-1 schedule, the ASPEN EO-1 agent will either accept or refuse the observation request.

A key point is that our sensorweb architecture is fractal in that science agents may themselves be sensorwebs, planning agents may be sensorwebs, each of the components may be a more complex architecture in itself. Because of this our architecture can be considered a system of systems.

3 Space-based Volcano Monitoring Sensorweb

This sensorweb architecture has been implemented in a general space-based volcano monitoring sensorweb with a number of space and ground components. In this instance, we utilized a number of science agents:

1. MODVOLC [Wright et al, 2003, 2004] and GOESVOLC [Harris et al, 2000] space-based detection systems
2. Two semi-manual advisory systems, the international volcanic ash advisory system (VAAC) [VAAC] and United States Air Force Weather Advisory System (AFWA) [AFWA] with on-line archiving and dissemination of volcanic advisories, and
3. Integration with existing in-situ sensor systems at the Kilauea (Hawaiian Volcano Observatory/USGS) and Mount Erebus, Antarctica (Mount Erebus Volcano Observatory/New Mexico) that produced notifications of triggering events.

Scientist defined triggers based on these inputs to cover campaigns for sustained observations of the Kilauea, and Mount Erebus volcanoes. Based on these campaigns, numerous EO-1 Hyperion observations were acquired of these and other volcanic targets. As part of the sensorweb campaigns, EO-1 also acquired imagery of flooding, wildfire, and other science events, in all totaling over 2300 observations (see ase.jpl.nasa.gov for current totals).

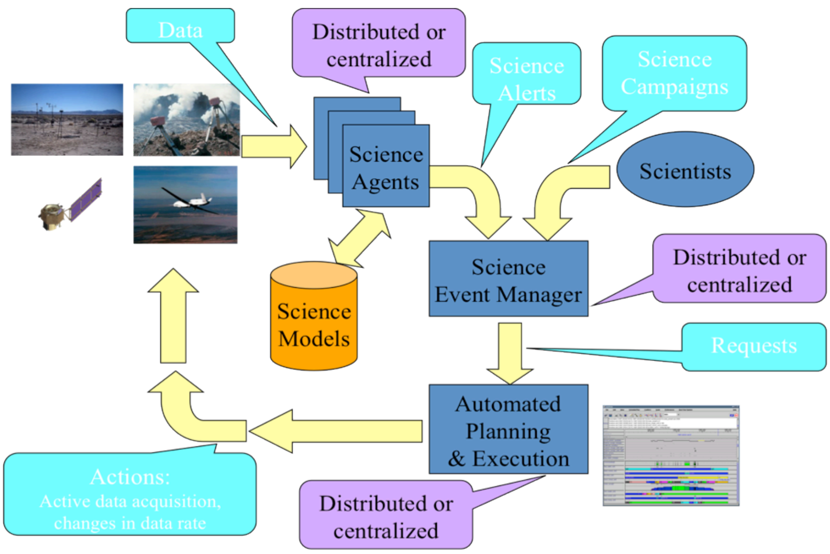

Figure 1: General Sensorweb Architecture

Within this EO-1 sensorweb, the EO-1 tasking agent uses the ASPEN automated mission planning system [Chien et al. 2000] customized for the EO-1 mission planning constraints [Chien et al. 2010]. The EO-1 adaptation of ASPEN takes into account a number of constraints in determining whether or not an observation can be taken:

Priority – the spacecraft may already be tasked to acquire a higher priority scene at a conflicting time (either directly overlapping or through one or more of the below constraints).

Visibility – even though the spacecraft might be unused it might not be able to see a desired science target.

Pointing/maneuver – the spacecraft takes time to move from pointing at one target to the next and must allow time for the

spacecraft to stabilize after pointing to enable precise imaging.
Thermal – the instruments have minimum and maximum temperatures at various locations that must be met to acquire valid science imagery. The minimums mean that warmup activities are required. The maximums mean that too many consecutive images will overheat the instrument.
Data volume – the spacecraft can only store a limited number of observations onboard.
Downlink – the spacecraft can only downlink at pre-scheduled times and overflights of fixed ground stations
Mode – various spacecraft subsystems have operational modes that must all be carefully selected and achieved for valid operations.
Only if all of these constraints can be satisfied can the EO-1 spacecraft acquire the requested scene.

4 The Mount Saint Helens In-situ Network

In 2005, the Optimized Autonomous Space In-situ Sensorweb (OASIS) project [Huang et al. 2010] was initiated to develop and demonstrate an integrated space in-situ sensor network for volcano monitoring. The OASIS project consists of two main components: 1. the hardware, physical sensor network, and software running on the spiders, and 2. The software for interpretation, command and control of the integrated network.

Figure 2: Each 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.

The Spider Sensors

As part of the OASIS project, the Cascade Volcano Observatory (CVO) of the United States Geological Survey (USGS) designed a network of "spider" sensors including data acquisition, sensors, and communication (see Figure 2). The spiders carry several COTS sensors including 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. Communication between nodes uses IEEE 802.15.4 ISM spread spectrum and smart mesh network technologies developed by WSU. 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.

OASIS Command and Control

OASIS incorporates existing real-time volcano monitoring and data-processing tools used by the USGS into the development of the command and control element as well as new software added to the USGS suite - the VALARM real-time data analysis and triggering software module. Using these tools the OASIS in-situ element can 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 and reprioritization of data is made by smart sensing components in node software, as well as the command and control element, following rules prescribed by a domain expert. For example, detection rules for seismic events inflation, or ash detection events can re-allocate bandwidth by instructing nodes to collect at a higher data rate or prioritize their data using a higher priority. 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.

Network management algorithms use 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 the VALARM software to trigger reconfiguration. However, the command and control center also provides a “manual” override option 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.

OASIS incorporates an information exchange system between space assets and other in-situ sensor webs anchored in OGC SWE web service interface [OGC SWE], relying heavily on Sensor Alert Services for inter-operation. 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 and EARTHWORM). 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.

5 Integrating Space and Ground Networks

We have demonstrated in OASIS feedback between ground and space operations. This capability is useful for several reasons:

• Space-derived information can increase the efficiency of operations of the in-situ element by enabling broad spatial scale information to be incorporated into operations decisions.
• Space-derived information can be used to trigger an in-situ deployment (or enhancement) at an unmonitored or poorly monitored volcano, minimizing resources required for constant monitoring.
• Feedback from in-situ instrumentation can provide valuable information (e.g. triggers) on highly constrained remote sensor operations (e.g. spacecraft assets in high demand).

Coordination between space and ground sensors can provide 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 Sensorweb 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 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 (e.g. VALARM). In this manner the OASIS ground network allows for powerful processing of in-situ data to task space assets (e.g., OASIS sensors, VALARM processed alerts, triggering EO-1 observations).

The integrated space, in-situ sensorweb represents a multi-agent framework in which individual nodes, or subnetworks can be viewed as collaborating agents and the messages that they send to eachother represent goals and beliefs as to the state of the world. In this perspective, individual and coordinating agents have policies designed to track specific types of scientific phenomena (e.g. volcanic events) and are acquiring data, processing data, and requesting additional data acquisition in concordance with these policies.

A unique innovation of OASIS is feeding back information from space observations into the in-situ element. High spatial resolution data generated by EO-1’s Hyperion instrument [Davies et al. 2006] is fed through thermal analysis processing software to detect a region of thermal activity on the target area (e.g. Mount St Helens), the data is analyzed, and the results pushed 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”

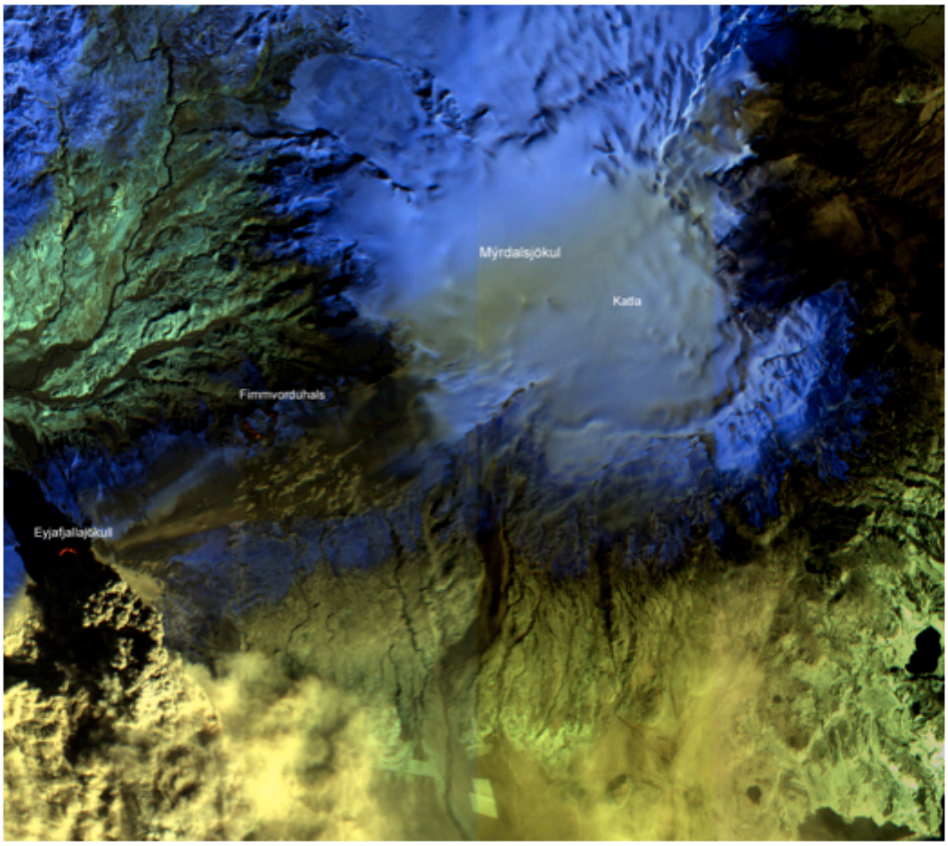

Figure 3:
EO-1 ALI false color imagery of Iceland volcanoes acquired 17 April 2010 via Volcano Sensorweb.

Image courtesy EO-1/NASA GSFC Volcano Sensorweb JPL/A. Davies

is processed by the command and control, which will re-prioritize bandwidth allocation.

6 Tracking Activity in Iceland 2010

The capabilities of the space-based network were highlighted during the recent (2010) eruptions of the Fimmvorduhals and Eyjafjallajokull volcanoes in Iceland in the Spring of 2010 [JPL 2010]. Initial detection and alerts via the MODVOLC monitoring [Wright et al. 2004] as well as other sources enabled tracking of the continuing activity. Figures 3 & 4 show imagery acquired using the EO-1 satellite and imagery and products distributed to local Icelandic parties as well as other operational parties.

7 Future and Related Work

Based on the successful deployment of the sensor spiders to Mount Saint Helens, the USGS is evaluating the spiders for potential deployment to other volcanoes. Based on the successful use of NASA space assets to monitor volcanoes, NASA is investigating the use of future NASA missions to increase spaceborne volcano monitoring. In the near term efforts are underway to try to integrate other space sensors such as Formosat and European Space Agency assets. This same general sensorweb concept is being applied to a range of other disciplines including flooding [Brakenridge and Anderson 2005, Carroll et al. 2009], oceanography [Chien et al. 2009], wildfires, and cryosphere.

8 Conclusions

We have deployed an in-situ network of sensors to the Mount Saint Helens volcano. This network includes a number of "spider" sensors, each of which has a seismometer, GPS receiver, infrasonic sensor, and lightning sensor. These sensors self form a network with both within node smarts and network wide smart capabilities and support interactive command and control with external components such as VALARM (at the USGS) and NASA EO-1.

These in-situ sensors have been integrated with an existing space borne volcano monitoring sensorweb focused on the Earth Observing One spacecraft. This linkage to space assets has demonstrated ground-based event detection triggering spaceborne observations as well as space observation triggering reconfiguration of the ground network. The interfaces between ground and space segments have demonstrated multiple aspects of the Open Geospatial Consortium (OGC) Sensorweb Enablement (SWE) web service standards. The successful linkage of space and ground elements of a volcano monitoring sensorweb show great promise to enhance future volcano monitoring and study.

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Thermal signature
Analysis estimate 2 GW

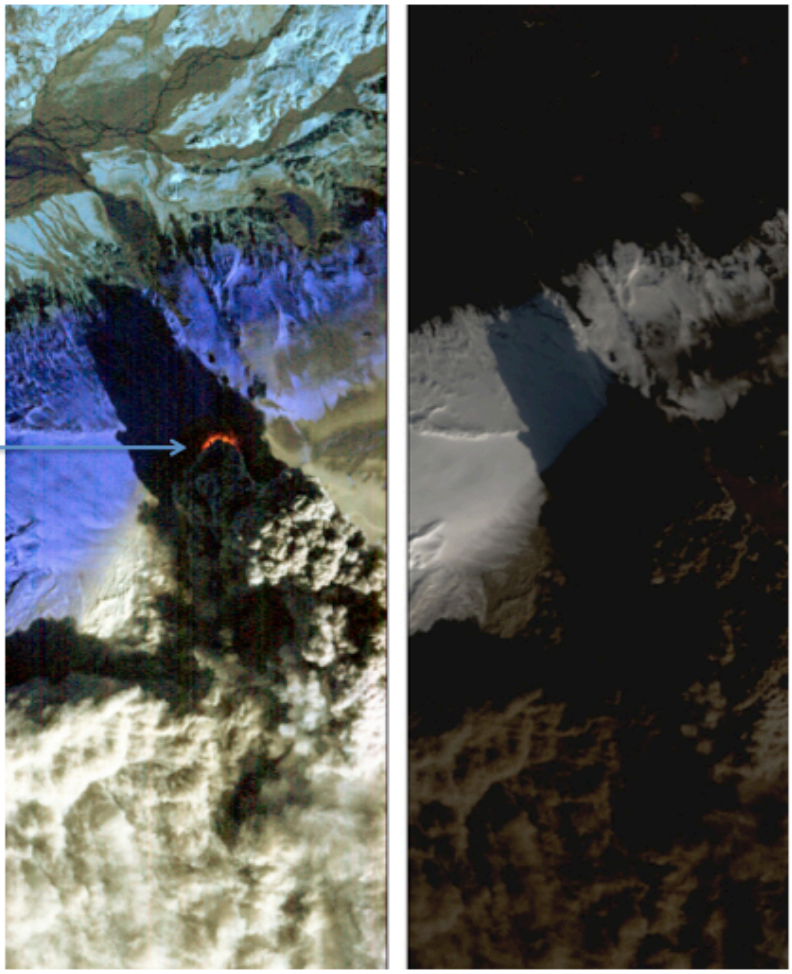

Figure 4:
Hyperion 17 April 2010
imagery acquired via
volcano sensorweb.
Left – thermal false color
Right – True color

Image courtesy
EO-1/NASA GSFC
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