The Model-Based Volcano Sensor Web: Progress in 2007

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***Abstract*— The autonomous Model-based Volcano Sensor Web (MSW), based at JPL, proved its worth during a volcanic crisis at Nyamulagira, Democratic Republic of Congo, in 2006. The MSW facilitated the rapid acquisition of spacecraft data which allowed pinpointing the location of the volcanic vent. This was vital in predicting lava flow direction and extent. In 2007 a number of improvements have been made to the MSW. These include the deployment of *in situ* SO_2 sensors on Kilauea volcano, HI, capable not only of triggering requests by the *EO-1* spacecraft in the event of anomalous SO_2 detection, but also of being triggered autonomously by an anomalous thermal detection from advanced data processing software onboard *EO-1*, and the conversion of the sensor web to using Open Geospatial Consortium Web Services. The Sensor Web is monitoring volcanoes around the world. A number of interesting volcanic eruptions have been detected and monitored, including a carbonatite eruption at Oldoinyo Lengai, Tanzania, and the March 2008 summit eruption of Kilauea, Hawai'i, that occurred in the Halema'uma'u caldera.**

I. Introduction

Deployment of smart sensors in space and on volcanoes can provide a means to rapidly generate an alert in the event of an eruption, when time is of the essence. Such alert can be used to govern the subsequent operations not only of the sensors but of other assets. The Model-based Volcano Sensor Web (MSW) is a project based primarily at NASA's Jet Propulsion Laboratory, and utilizes smart sensors to improve reaction times during a volcanic crisis. Volcanic eruption products, both on the ground (lava flows, pyroclastic flows, lahars) and in the atmosphere (ash and gas plumes) can pose serious threats to life and property. The problems are most acute with remote volcanoes (where there is little or no *in situ* monitoring capability) and volcanoes in regions where poor infrastructure and even civil strife impacts the ability of scientists in the field to assess volcanic hazard and risk. In both cases, remote sensing of volcanoes from space-based platforms is often the first indication that magma has reached the surface, and an eruption is in process. At the Jet Propulsion Laboratory we are developing an advanced sensor web that utilizes models of volcanic activity to recognize not only the stage of an eruption, but to seek out specific additional data needed to improve the knowledge of the eruption state. By "state" we mean a deep understanding of the eruption process based on physical models of how the volcano behaves, combined with remote and *in situ* observations that further constrain state, and (ideally) subsequent eruption behaviour. A simple example of this would be to monitor effusion rate to determine if the eruption is waxing or waning.

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II. Model-Based Volcano Sensor Web (MSW)

The first Volcano Sensor Web (VSW) developed at JPL has been described by Chien *et al.* (2005a) and Davies *et al.* (2006a). A new, expanded sensor web is described by Davies *et al.* (2007, 2008a). In brief, a wide range of detections (alerts) of volcanic activity, or of impending volcanic activity, are used to trigger observations from the Earth-orbiting *Earth Observing-1* (*EO-1*) spacecraft. Alerts come from autonomous systems processing spacecraft data on the ground, web postings of detections of volcanic ash and plumes, *in situ* instruments, emails detailing volcanic activity, and from data processing applications onboard *EO-1* (i.e, ASE, described below). In late 2007, two autonomously-operating "Volcano Monitor" gas sensors, which are capable of two-way autonomous triggering and response (see section IX), were placed on Kilauea volcano, Hawai'i.

As noted by Davies *et al.* (2007), our new sensor web (Figure 1) is an advance beyond a simple detection-response operation mode, where an alert of activity generated a request for a spacecraft observation with, generally, no deeper understanding of the magnitude or extent of the eruption that was taking place. The priority of the observation request was determined by rank in a table. The highest priority targets were those where either an eruption would have a potentially catastrophic impact (e.g., Mauna Loa, Vesuvius), or were of particular scientific interest (Erta 'Ale, Erebus).

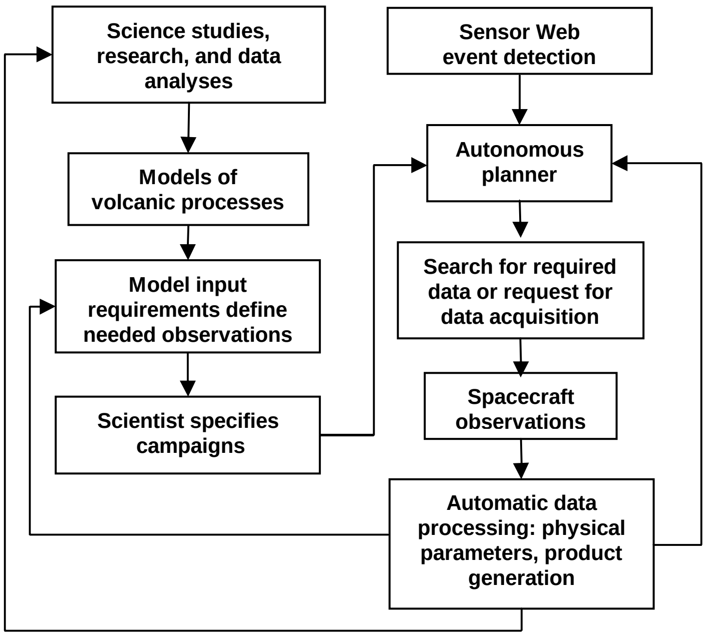

Figure 1. Layout of the Model-based Volcano Sensor Web (from Davies *et al.*, 2007). An alert of volcanic activity drives a request for data to be input into models of volcanic processes to gain a better understanding of the event taking place. Data are searched for: if not available, then assets are retasked to obtain the data. For example, detection of a volcanic plume leads to a request for data at short- and thermal-infrared wavelengths in order to estimate effusion rate.

The ultimate goal of the new MSW is to have asset operations based on determining what information is needed to understand the state of an eruption, identifying what additional data are needed to improve knowledge of the volcano state. The required information flow between sensor web assets is enabled using OGC Web Services, discussed in section XII.

The MSW consists of several parts: (a) a model of the physical processes under study; (b) Web Service models of a set of sensors which describe the data being acquired as well as tasking interfaces; (c) a set of *in situ* and remote sensors together with their tasking interfaces; (d) an instrument data processing capability for processing data based on web service-defined search descriptions, to provide physical model inputs; (e) a web-based data display and evaluation application at JPL; and (f) command and control infrastructure to enable automated tasking of in-situ and remote sensing assets. Eventually we will demonstrate a sensor web using data collection assets and applications processing these data at JPL (*EO-1* Hyperion and Advanced Land Imager [ALI] data), the University of Hawai'i (MODVOLC, processing Moderate Resolution Imaging Spectroradiometer [MODIS] infrared data), and at the Mount Erebus Volcano Observatory (MEVO - New Mexico Tech.). MEVO provides multi-sensor data of volcanic activity at the Erebus volcano, Ross Island, Antarctica.

III. Remote Sensing of Volcanic Activity

Both the original Volcano Sensor Web and the MSW make use of Earth-orbiting platforms and autonomous data processing systems. The flight of the first Earth-orbiting high-spatial-resolution hyperspectral imager, Hyperion (Pearlman *et al.*, 2003), and ALI on *EO-1* (Ungar *et al.*, 2003); and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (Yamaguchi *et al.*, 1998), the high-spatial-resolution multispectral (visible and infrared) imager on *Terra*; and MODIS on *Terra* and *Aqua*, yield observations of volcanoes at spatial resolutions as high as 10 m per pixel (ALI), temporal coverage up to four times a day or better for high-latitude targets (MODIS), and spectral resolutions of 10 nm (Hyperion has 196 usable, discrete bands from 0.4 to 2.5 µm, covering visible and short infrared wavelengths). The proliferation of orbiting sensors in the last few decades has increased the pace of data acquisition dramatically. This has led to the development of automated systems to process and mine the huge volumes of data collected for the nuggets of high-value science content. Direct broadcast of satellite imaging data, for example, from MODIS, bypasses traditional routes of data transmission via a small number of ground-stations, and has been coupled to automatic data-processing applications to rapidly detect anomalous (above-background) thermal emission.

Two such event detection systems are based at the University of Hawai'i. MODVOLC (Wright *et al.*, 2004) processes daily MODIS data; and GOESvolc (Harris *et al.*, 2000) processes GOES (Geostationary Operational Environmental Satellite) data from the Pacific Rim at lower spatial, but higher temporal (15-minute) resolutions. Although MODIS collects data only four times a day (with higher temporal resolution at high latitudes) it has the advantage of global coverage over GOES.

The recognition and posting of the location of volcanic thermal activity by MODVOLC is currently about 24 hours after data acquisition.

IV. Onboard Data Processing And Spacecraft Autonomy: ASE

The notification speed of the detection of high-temperature anomalies on the surface has been greatly increased by placing data analysis software onboard the spacecraft. The NASA Autonomous Sciencecraft Experiment (ASE), under the auspices of the NASA New Millennium Program (Space Technology 6) has been in full operation onboard *EO-1* since 2004. ASE (Chien *et al.*, 2005b; Davies *et al.*, 2006b) is software that processes data from the Hyperion hyperspectral imager, an instrument well-suited to detecting thermal emission from on-going volcanic activity (e.g., active lava flows or domes). Apart from data processing, ASE consists of a planner that allows re-tasking of the spacecraft to re-image targets of interest, and also a spacecraft command language that allows the science goal planner to operate spacecraft and instruments. Rapid responses, at best within a few hours of initial observation acquisition, have been obtained by ASE.

Of particular interest is the ASE THERMAL_SUMMARY product (Davies *et al.*, 2006a, 2006b). This ASE product consists of spectra (the intensity of thermal emission at 12 wavelengths) for each hot pixel identified in the Hyperion data by the ASE thermal classifier. The file, no larger than 20 kB in size, is downlinked with spacecraft telemetry at the next contact. Often, these data are posted at JPL within 90 minutes of acquisition, allowing rapid identification of volcanic activity (or at least of a thermal source on the ground: ASE has detected burning fields, forest fires, oil fires and industrial processes that generate intense thermal sources). In terms of the location of the eruption, at this time in the process, information as to the precise pointing of *EO-1* is limited, so all that can be said is that a thermal source has been detected. This is sufficient to issue a bulletin that a thermal source has been successfully identified in the data. More precise location has to wait until the full Hyperion observation is downlinked and processed.

The THERMAL_SUMMARY product, with radiance data in the range 0.4 to 2.4 μm, can also be processed with ground-based applications to determine the intensity of thermal emission and extent of activity. Now, in part due to NASA AIST Program support, and with the invaluable help of the USGS EROS Data Center and Goddard Space Flight Center, downlink and transfer of raw Hyperion data to JPL has been reduced from more than two weeks in 2004 to about 24 to 36 hours. Another advance is the implementation in 2007 of automatic processing of *EO-1* Hyperion data to Level 1G. These are data that are geo-rectified, utilizing spacecraft telemetry and image metadata to determine exact spacecraft pointing. The result is that, typically within about 24 hours of acquisition, data are in a format where the thermal sources can be overlain on a map or photo of a volcano to identify the location of activity.

The next sections describe a sample of Sensor Web operations and observations during 2006, 2007 and 2008.

V. Nyamulagira, D. R. Congo, December 2006

The MSW's capability for providing crucial data in the midst of a volcanic crisis was demonstrated in December 2006 during the eruption of Nyamulagira volcano (a.k.a. Nyamuragira), located at longitude 29.2 E, latitude 1.41 S in the Democratic Republic of Congo, Africa (Davies *et al.*, 2007, 2008a; Scott, 2008). Shortly after an eruption began in November 2006 an alert from the Volcanic Ash Advisory Centre (VAAC) in Tolouse, France, was autonomously detected by the MSW and triggered an observation by *EO-1*. Within two hours of data acquisition, the data had been processed onboard by ASE, the thermal classifier had detected hot pixels, *EO-1* was retasked to obtain another observation on 7 December 2006, and the THERMAL_SUMMMARY product had been downlinked and was available at JPL for study. Although this product is not suitable for accurate geolocation of activity, it was nevertheless an indication that the eruption had been successfully imaged. The full dataset arrived a day later. Within hours, the data were hand-processed and the vent location identified and transmitted to Paolo Papale and colleagues at INGV (Italy). Papale *et al.* modeled likely flow direction and extent in order to determine risk to local towns (Figure 2), allowing authorities on the ground to plan and allocate resources accordingly. During this particular volcanic crisis, the output from the sensor web thus proved to be of high value (Davies *et al.*, 2008a; Scott, 2008). Thankfully, the eruption was relatively short-lived, and lava flows never reached the town of Sake. Nevertheless, the MSW was shown to be a potential life-saver.

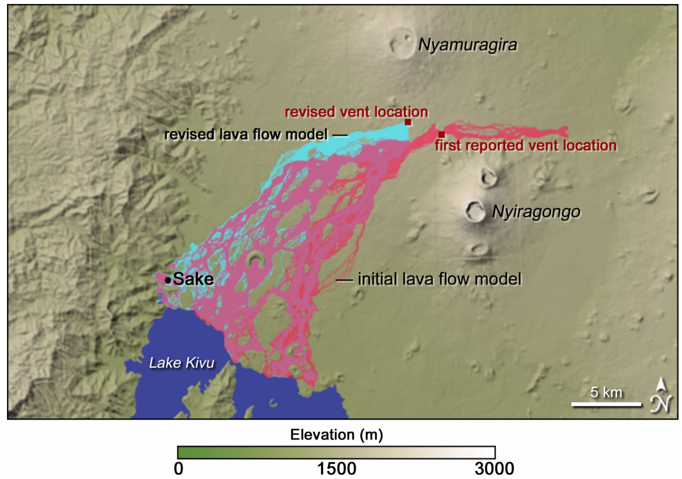

Figure 2. The Nyamulagira eruption of November 2006: model flow predictions by P. Papale and colleagues at INGV, Italy, based on two estimates of vent location. Red = original flow model based on estimate of vent location. Note flows heading east. Blue = flow model based on *EO-1* vent location. No flows head east. More flows reach the town of Sake. Purple = where model outputs for both vent locations overlap. Image credit: Jesse Allen, NASA. See Scott (2008).

Steps are now being taken to fully automate the entire data flow. This includes setting up a website where alerts from Goma Volcano Observatory can be posted, either automatically from sensors, or by hand. Alternatively, email alerts, in pre-determined format, can be posted. The account inbox would be periodically interrogated by a remote agent to detect an alert posting. Whether posted on a website or contained in an email, the text is parsed and the target identified. A request is passed to the *EO-1* planner. After data acquisition, processing and hot spot identification and geolocation, the final steps in data flow, at least as far as hazard notification efforts require, are to (1) plot the location of hot pixels on a high-resolution image or map, and (2) automatically post these products on a web page as well as via email to volcanologists in the field.

VI. Manda Hararo, Ethiopia, Aug-Sept 2007

In August and September 2007, Manda Hararo (long. 40.82 E, lat. 12.170 N) in the Afar region of Ethiopia was imaged as a result of Sensor Web operations. In late August 2007, reports were received that an eruption was taking place in this remote region. Triggered by a MODVOLC thermal detection, *EO-1* was retasked to obtain higher spatial and spectral resolution data. Additional observation requests were input by an operator at JPL. Unfortunately, the vent location and area covered by new lava flows were repeatedly covered in cloud in the Hyperion and ALI data (Davies *et al.*, 2008a).

VII. Oldoinyo Lengai, Tanzania, August 2007

On 29 August 2007 *EO-1*, triggered by a MODVOLC thermal detection, imaged Oldoinyo Lengai volcano (long. 35.902 E, lat. 2.751 S), in the East African Rift Valley in Tanzania (Davies *et al.*, 2008a). Oldoinyo Lengai (Figure 3) is a volcano of particular interest as it is the only volcano known to have erupted natro-carbonatite lavas in historical times. These lavas are erupted at a relatively low temperature (600 ºC), many hundreds of degrees less than that of basalt lava (typically 1150 ºC) (Pinkerton *et al.*, 1995).

Figure 3. Oldoinyo Lengai, Tanzania, erupting in 1966. Image credit: Global Volcano Network.

It was not known whether such an eruption could be detected by ASE because Hyperion is not particular sensitive to this lower-temperature volcanism. Although a number of day and nighttime observations were obtained from 2004 to 2007, no thermal anomaly was detected. Excitingly, the August 2007 Hyperion data showed two very bright sources in the summit crater with spectra consistent with hot, newly-erupted lava. There was an indication of a short lava flow flowing northwest from the crater. Based on a preliminary analysis of the Hyperion data, effusion rate at this time was estimated at ~0.5 $m^3 s^{-1}$. Such effusion rate calculations are now being incorporated into the Sensor Web as a generated product for each observation.

VIII. Halema'uma'u, Kilauea, HI, USA, March 2008

Although Kilauea volcano, Hawai'i, has a reputation for gentle, quiescent emplacement of basalt flows, explosive activity took place in 1790 and 1924 and at many other times in the past (e.g., Swanson, 2007). On 19 March 2008, after a period of greatly-increased SO_2 production both at the Halema'uma'u (an impressive caldera set into the floor of the larger summit caldera of Kilauea) and the Pu'u 'O'o vent, an explosion took place in the wall of Halema'uma'u. Debris from the explosion showered down over an area of some 75 acres (see USGS Hawaiian Volcanoes Observatory eruption updates for March 2008 at http://hvo.wr.usgs.gov). Thermal emission from the new vent triggered MODVOLC alerts which were detected by the MSW. The MSW was unable to retask *EO-1*, but *EO-1* nevertheless imaged Kilauea's summit on 20 March 2008 as part of a routine sequence of observations (it was the presence of these observations that prevented *EO-1* rescheduling by the MSW!). This observation of a different part of the Kilauea summit area also included the relatively small Halema'uma'u vent, which by now was emitting a dense plume of gas, ash particles and the occasional small blob of molten lava (Figure 4).

Figure 4. 20 March 2008: volcanic activity at the summit of Kilauea volcano, Hawai'i. Image credit: United States Geological Survey-Hawaiian Volcanoes Observatory.

The MSW Hyperion data processing algorithms generated a number of products from this observation, starting with the THERMAL_SUMMARY product. The full dataset was processed to avoid saturated wavelengths, to remove incident sunlight (this was a daytime observation), and to perform temperature fits to the remaining data. The methodology for this data processing is described in Davies *et al.* (2008b).

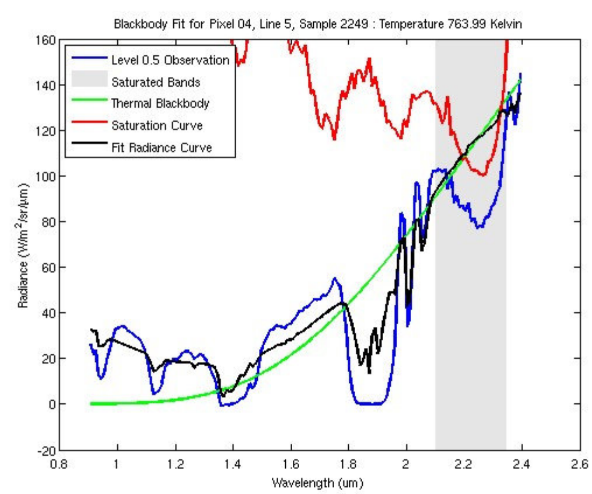

Figure 5. 20 March 2008: MSW processed *EO-1* Hyperion observation EO1H0620462008080110KP and fitted the data with a thermal emission model.

The ASE THERMAL_SUMMARY product identifies all hot pixels in an observation. For each hot pixel, data are processed to calculate the temperature of the thermal source (determined from the shape of the thermal emission spectrum) and the area (often sub-pixel) of the thermal source. A Hyperion pixel has an area of 900 m^2 (Davies *et al.*, 2006b). An example is shown in Figure 5 for the most intense pixel in the 20 March 2008 observation, which was later found to be co-incident with the new vent. Figure 6 and Figure 7 show the temperatures and pixel fractional areas for all hot pixels identified in the 20 March 2008 THERMAL_SUMMARY product. Only two pixels have a high temperature and a relatively high pixel fraction (> 0.2) filled. The other pixels are almost certainly subject to thermal blooming, where adjacent Hyperion detectors pick up excess thermal emission from a very intense, partially-saturated detector.

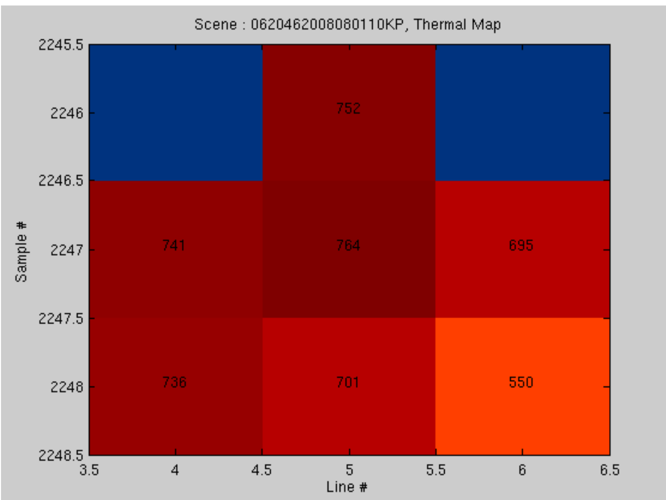

Figure 6. Temperature derivations (K) from hot pixel spectra identified in Hyperion observation EO1H0620462008080110KP, obtained 20 March 2008. The new vent is at a temperature of at least 764 K.

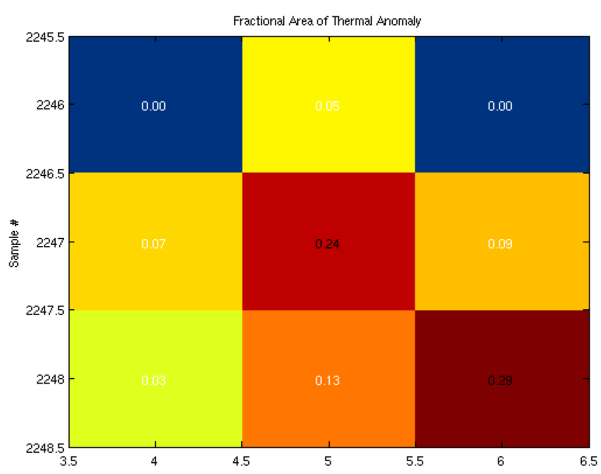

Figure 7. Pixel fractional area derivations for hot pixels identified in Hyperion observation EO1H0620462008080110KP, obtained 20 March 2008.

The hottest source, at 764 K, has an area of 220 m^2. Adjacent pixels have temperatures of 550 K (261 m^2) and 701 K (117 m^2). Knowing temperature and area, thermal emission is calculated and integrated. The two hottest pixels yield a total thermal emission of 2-5 MW. The three hottest pixels yield a total thermal emission (from the vent and from the hot plume) of ~4-8 MW. A goal of the MSW is to gain a deeper understanding of volcanic processes being observed. Therefore, using this automatically generated product (integrated thermal emission), the next step in MSW development will be to link, using models, the observed thermal emission to the source of the heat: molten magma beneath the surface - and then to the supply of magma from an even deeper source (a magma chamber).

The 20 March 2008 temperature and power data were transmitted to the Hawaiian Volcanoes Observatory (HVO) in response to a request for information (J. Kauahikaua, 2008, pers. comm.)

IX. Volcano Monitors

The current Sensor Web demonstrates the retasking of a spacecraft as a result of detection of an alert. The reverse is also possible, triggering an *in situ* sensor as a result of event (eruption) detection from a spacecraft. Such autonomous sensor-to-sensor communication via a data-clearing hub has applications elsewhere in the Solar System, where nets of spacecraft, rovers and aerobots can communicate discoveries to optimize science return, and to safeguard assets. One example of this would be a detection of a martian dust-storm from on-board analysis of data on an orbiter. A storm warning is then automatically sent to assets on the martian surface or in the atmosphere.

Under an expansion of the sensor web, such two-way data flow between sensor and spacecraft is now being demonstrated after the installation of two sensor packages on Kilauea volcano, Hawai'i, in November 2007 (Boudreau *et al.*, 2007). Each expendable Volcano Monitor contains a SO_2 sensor. The two monitors have has been placed downwind of the Pu'u 'O'o vent of Kilauea, and are connected to the Sensor Web via Iridium modem, and thence to *EO-1*. In nominal (low) power conservation mode, data from these sensors are collected and transmitted every hour to the Sensor Web through the Iridium Satellite Network. If SO_2 readings exceed a predetermined threshold, the Sensor Web triggers a request for prompt *EO-1* (Hyperion) data acquisition, and transmits a signal to the Volcano Monitor to increase the sensor data acquisition rate, increasing their sampling frequency to once per minute (high power "burst mode"). Autonomous control of the sensors' sampling frequency enables the Sensor Web to monitor and respond to rapidly evolving conditions before and during an eruption, and allows near real-time compilation and dissemination of these data to the scientific community (Boudreau *et al.*, 2007). It is hoped that this "two-way" demonstration will be performed during the summer of 2008. Data are posted and archived at JPL, and access to the website made available to HVO and the National Park Service (Hawai'i Volcanoes National Park)

X. Model-Driven Sensor Web Operations

Additionally, we are incorporating models of volcano behaviour to make the best use of available resources. We are studying sensor data, obtained remotely and from *in situ* instrumentation, from Erebus and Kilauea volcanoes in order to determine thresholds delineating unusual levels of activity. These thresholds will allow events of particular interest (either the cessation of activity, or an unusually high level of activity) to be distinguished from the usual (background) level of volcanism. A threshold could range from a count of the number of alerts in a 24-hour period (from *in situ* instruments), or an unusual level of thermal emission detected from a spacecraft, to results from use of more sophisticated models of volcanic processes. For example, we are developing a Sensor Web plug-in module that uses a model of how eruption effusion rate (volume of lava erupted per second) varies with time (Wadge, 1981). Plotting such variability can be used to estimate the possible magnitude of an eruption episode, the lava volume erupted, and even, possibly, the likely duration of the event.

XI. SensorML and Web Services

SensorML is an XML encoding protocol (e.g., Botts *et al.*, 2006) which allows definition of processes, assets and products. SensorML applications enable (a) the extraction of higher-level information from datasets; (b) the exchange of metadata, including information pertaining to the quality of the data; and (c) exchange of instrument and data information. SensorML services (see below) allow information transfer between sensors, and are used to discover additional assets, data, and products to increase knowledge of the process state under scrutiny.

To enable efficient data flow and identification of assets, data, processes and products we use *Web Services* as a framework, not only for efficient management of the current sensor web, but as a means and a template for expanding the system to include new assets and products and to interface with other sensor webs. Our ultimate goal is a globe-spanning sensor and asset system that autonomously reacts to dynamic event detection and seeks out existing data to understand the process taking place. If these are unavailable, then assets are sought to provide the needed data. Our services are:

Sensor Planning Service (SPS): used to determine whether a sensor is available to acquire data.

Sensor Observation Service (SOS): used to retrieve engineering or science data from the SPS.

Web Processing Service (WPS): used to perform a calculation on the acquired remote sensing data.

Sensor Alert Service (SAS): used to publish and subscribe to alerts from space, air, and ground assets.

XII. Other Sensor Web Activities

In addition to the Volcano Sensor Web, other sensor web operations are currently taking place. These include retasking *EO-1* to observe areas of snow and ice melting or freezing, based on the analysis of ice coverage data disseminated by the National Snow and Ice Data Center (NSIDC), Denver, CO. This part of the sensor web project is overseen by Thomas Doggett at Arizona State University. A Flood Sensor Web is now being tested, where *EO-1* is triggered from automatic processing of NASA Tropical Rainfall Measuring Mission (*TRMM*) data coupled to hydrological modeling. This effort is led by Felipe Ip at the University of Arizona.

XIII. Summary of Sensor Web Operations

Sensor Web remote-asset operations are ultimately limited by the availability of *EO-1*, a heavily-subscribed spacecraft. This potential problem is mitigated somewhat by the fact that volcanic thermal emission data are best obtained at night, greatly reducing potential conflicts. Table 1 shows the number of sensor web replacements made and other operational information. "Science scenarios" refers to the number of ASE observations obtained since May 2004. Sensor Web alerts have higher priority than ASE requests.

Table 1. ASE Mission Summary Data as of 13 May 2008

	mission	last week	yesterday	upcoming
EO-1 images taken	15869	97	17	24
Sensor web	2113	6	0	0
Science scenarios	1428	4	0	0
Ground contacts	15402	104	18	17
X-band	5227	31	7	6
S-band	10175	73	11	11
Planner goals	124430	665	101	130

XIV. Future Automated Re-Tasking

A key element of this new sensor web technology and philosophy is automated re-tasking. In the existing sensor web, automated planning technology is used to automatically re-task sensor web assets (primarily *EO-1*). This capability is hard-wired such that the scientist must specify the exact combination of sensor events that causes a specific sensor web reconfiguration (usually a request for one or more observations by *EO-1*).

In future, this capability will be generalized in several ways. Firstly, the *triggering events* will be generalized to enable triggers based on deeper models of the science phenomena (e.g. parameters of a physics–based model). These triggers include effusion rate estimation and temporal variability in eruption mode, and a change in eruption mode (e.g., effusive to explosive, gas to ash). Additionally, we will add the capability to respond with additional data collection based on class of sensor. For instance, consider a scenario where a specific thermal measurement might be requested, with SensorML specifications being used to seek out and assess available sensors and to retask appropriate assets.

Secondly, the *types of responses* will be generalized to new asset classes. We will demonstrate space-borne information leading to reconfiguration of ground assets as well as ground assets leading to reconfiguration of other ground assets. Thirdly, we will provide *basic optimization capabilities* to enable greater flexibility in representing scientist/response preferences. At first these will be restricted to single observation preferences (e.g., timing the duration of a single event in a sequence of observations obtained using trigger/response mode) but we will extend this to enable specification of preferences over a sequence of observations (e.g., a campaign with system-calculated intervals between observations to obtain the most useful sequence, based on the process taking place). Each of these technology advances will be demonstrated in the context of the volcano sensor web testbed which will link together space assets and ground assets.

Acknowledgments

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