# A Science Model-Driven Autonomous Volcano Sensor Web

Ashley Davies, Robert Wright, Philip Kyle, Rebecca Castaño, Steve Chien, Daniel Tran, Scott Chadde, Lukas Mandrake, Dan Mandl and Stuart Frye

***Abstract*— We are developing a model-driven sensor web in order to enable science-driven asset command and control. This not only will optimize resource use, but will also result in a more rapid response to alerts of volcanic eruptions.**

## I. Introduction

In a volcanic emergency, time is of the essence. The products from volcanic activity, both on the ground (lava flows, pyroclastic flows, lahars) and in the atmosphere (ash in volcanic plumes) can pose serious threats to life and property. The problem is 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 NASA's Jet Propulsion Laboratory we are developing an advanced sensor web that utilizes models of volcanic activity to recognize not only at what stage an eruption is in, but to seek out specific additional data needed to improve the knowledge of the eruption state. Such autonomous sensor webs have applications not just on Earth, but also on other planets (such as Mars), where the management of a large number of ground-based, atmospheric and orbiting assets need to be coordinated to minimize resource use and maximize science return.

## II. Model-Driven Volcano Sensor Web (MSW)

The Volcano Sensor Web at JPL has been described by Chien *et al.* (2005a) and Davies *et al.* (2006a). A wide range of alerts or detections 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, alerts from *in situ* instruments, emails detailing volcanic activity, and from alerts from data processing applications onboard *EO-1* (i.e, ASE, described below).

The new sensor web (Figure 1) is an advance beyond this simple detection-response operation mode, where an alert of activity generates 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).

The goal of the new MSW is to have asset operations based on determining what additional information is needed to understand the state of a volcanic 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 SensorML, which provides an XML encoding protocol (e.g., Botts *et al.*, 2006) for describing a process, enabling extraction of higher-level information from datasets, the exchange of metadata, the quality of the data, and instrument and data information, between sensors, and the discovery of assets, data, and data products and observation requests.

The MSW consists of several parts: (a) a model of the physical processes under study; (b) SensorML 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) instrument data processing capability capable of processing data based on SensorML 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. We will demonstrate a prototype 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 Hawaii (MODVOLC, processing MODIS infrared data), and at the Mount Erebus Volcano Observatory, MEVO, (New Mexico Tech.) which provides multi-sensor data of volcanic activity at Mt. Erebus, 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

A. G. Davies, R. Castaño, S. Chien, D. Tran, and L. Mandrake are at the Jet Propulsion Laboratory-California Institute of Technology, ms 183-501, 4800 Oak Grove Drive, Pasadena, CA 91109, USA (phone: 818-393-1775: email: Ashley.Davies@jpl.nasa.gov).

R. Wright is at the University of Hawai'i at Manoa, Hawai'i Institute of Geophysics and Planetology, 1680 East-West Road, POST 602, Honolulu, HI 96822, USA.

P. Kyle and S. Chadde are at the New Mexico Institute of Mining and Technology, Dep. of Earth and Environmental Science, Socorro, NM 87801, USA.

D. Mandl is at the NASA Goddard Space Flight Center, ms 584.0, Greenbelt, MD 20771, USA.

S. Frye is at Noblis, 3150 Fairview Park Drive South, Falls Church, VA 22042, USA.

# Model-driven Sensor Web

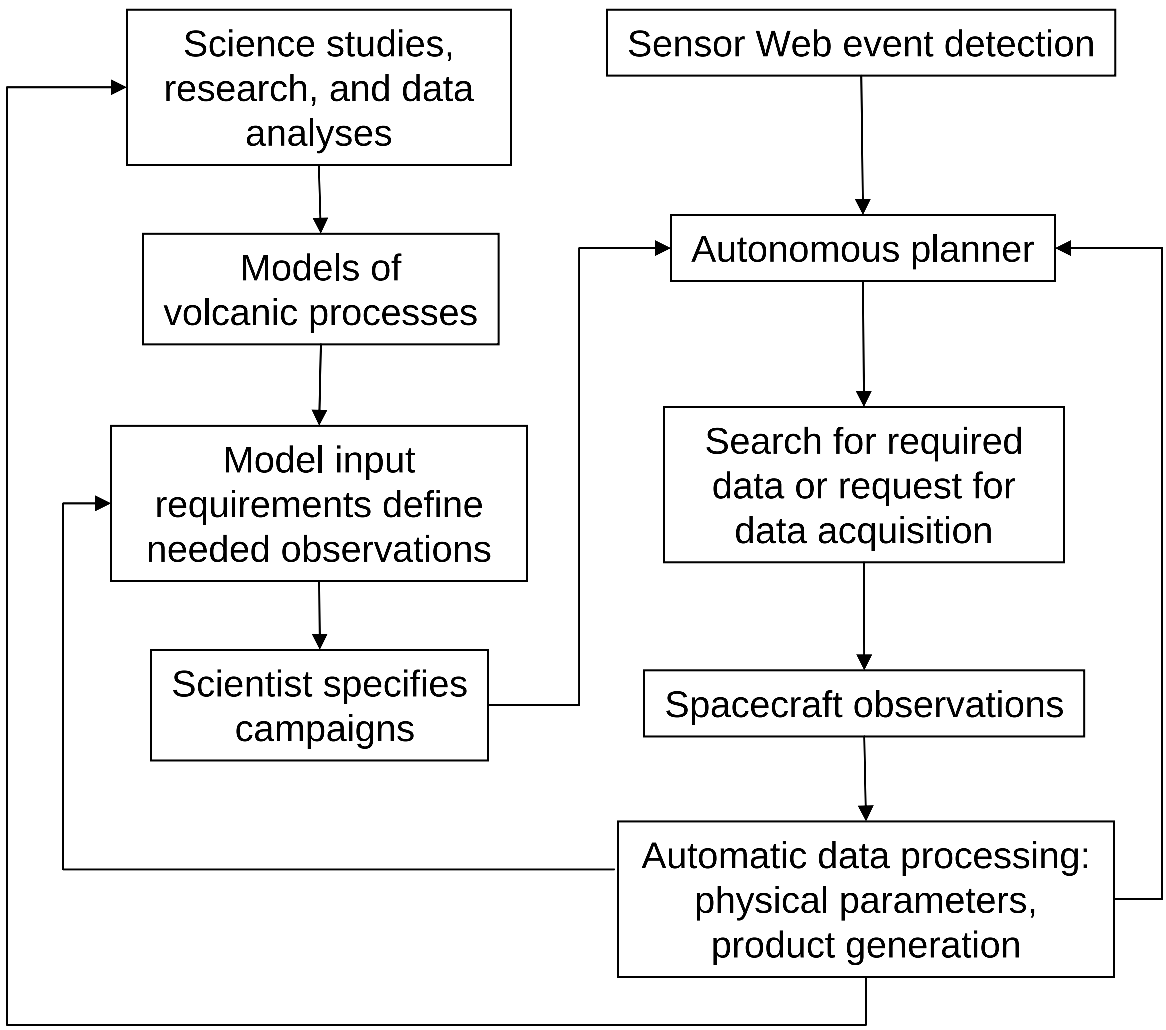


Figure 1. Layout of the Model-driven Volcano Sensor Web. An alert of volcanic activity drives a request for data to be input into models of volcanic processes to gain a better understanding of the event taking place. Data are searched for: if not available, then assets are retasked to obtain the data. 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.

processing systems. The flight of the first Earth-orbiting high-spatial-resolution hyperspectral imager, Hyperion (Pearlman *et al.*, 2003), and the Advanced Land Imager (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 the Moderate Resolution Imaging Spectroradiometer (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). In the last years of the 20$^{th}$ Century and early years of the 21$^{st}$, the proliferation of orbiting sensors has increased the pace of data acquisition dramatically, leading 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 detection systems are at the University of Hawai'i. MODVOLC (Wright *et al.*, 2004) processes daily MODIS data; and GOESvolc (Harris *et al.*, 2000), which processes GOES (Geostationary Operational Environmental Satellite) data from the Pacific Rim at lower spatial, but higher temporal (15-minute), resolution. MODIS has the advantage over GOES of global coverage four times a day, with higher temporal resolution at higher latitudes. The recognition and posting of the location of volcanic activity by MODVOLC is currently about 24 hours after data acquisition.

## IV. Onboard Data Processing And Spacecraft Autonomy: ASE

Notification 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 such data classifiers, ASE also 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 the ASE.

Of particular interest is the ASE THERMAL_SUMMARY product (Davies *et al.* 2006a, b). This is generated by ASE, and 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. This 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). Due to limited knowledge at this time as to the timing of the spacecraft observation, generally at this time 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. The THERMAL_SUMMARY product, with intensity data in the range 0.4 to 2.4 µm, can also be processed with ground-based applications to determine the intensity and extent of activity. Now, as part of the NASA AIST-funded work, 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 hours. At JPL, data are processed to L1G, that is, a geo-located format, utilizing spacecraft telemetry and image metadata to determine exact spacecraft pointing. The result is that within about 24 hours of acquisition, data are in a format where the thermal sources can be overlain of a map or photo of a volcano to identify the location of activity.

## V. Nyamulagira, December 2006

The capability for providing crucial data in the midst of a volcanic crisis was demonstrated in December 2006 during the eruption of the volcano Nyamulagira (a.k.a. Nyamuragira) located at latitude 1.41 S, longitude 29.2 E, in the Democratic Republic of Congo, Africa. During late October and November 2006 increased seismic activity, measured at the Goma Volcano Observatory (GVO), indicated an eruption was imminent (M. Kasereka, pers. comm., 2006). Magma reached the surface on **27 November 2006**, when lava erupted on the northeastern flanks of Nyamulagira forming lava fountains and lava flows. The glow from this activity was observed from Goma, some 30 km to the south (Smithsonian Institution, 2007). Volcanologists from GVO were unable to travel up to the vent to pinpoint its location, due to the local security situation. On **1 December 2006** an urgent call went out by email for satellite imagery to help understand the dynamics of the eruption. Eventually, a copy of this email reached JPL on **2 December 2006**. Using ground-based spacecraft operations planner similar to the planner flying on *EO-1*, it is a relatively simple task for an operator to identify and insert an observation into the spacecraft operations time line. Insertion depends on an observation slot being available, and also on the relative position of target and spacecraft. *EO-1* can observe equatorial targets approximately 10 times (5 day, 5 night) in a 16 day period. In this case, however, such a manual intervention was not necessary. The JPL Volcano Sensor Web had already been triggered. The volcanic plume emanating from Nyamulagira was reported by the Volcanic Ash Advisory Centre (VAAC) in Toulouse, France, and this alert was detected by the VSW. *EO-1* was autonomously

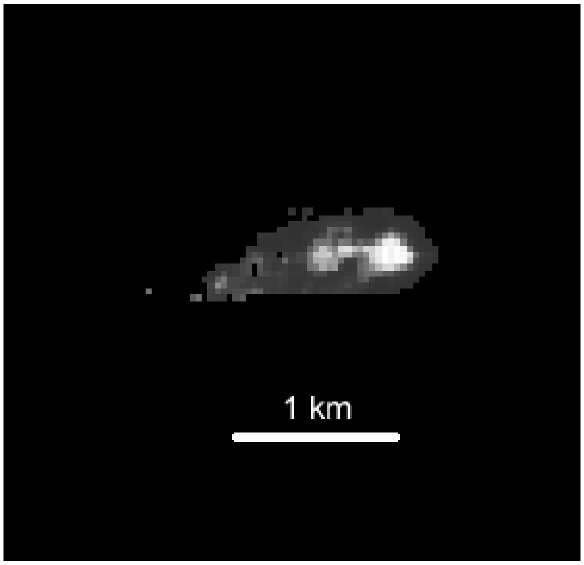


Figure 2 (above). Nyamulagira in eruption in late 2006. The eruption was detected by the ASE Thermal Classifier (Davies *et al.* 2006b), used to process *EO-1* Hyperion observation EO1H1730612006338110KF obtained on 4 December 2006. Image resolution is 30 m per pixel. The most intense group of pixels (white) denote the active vent, where lava first reaches the surface. Lava flows move to the west (from right to left). ASE rapidly downlinks the number of thermally-active pixels and 12 wavelengths of data for each of these pixels (to a file size limit of 20 kB). This image is at 1.245 µm. Location of the thermal source to within ~1 km along the spacecraft track vector is not possible with this product until spacecraft telemetry and metadata are returned, usually ~24 hours after data acquisition. Nevertheless, this product rapidly (typically 90 minutes after observation) confirms the eruption has been successfully observed. These data can be used to quantify thermal emission and constrain effusion rate.

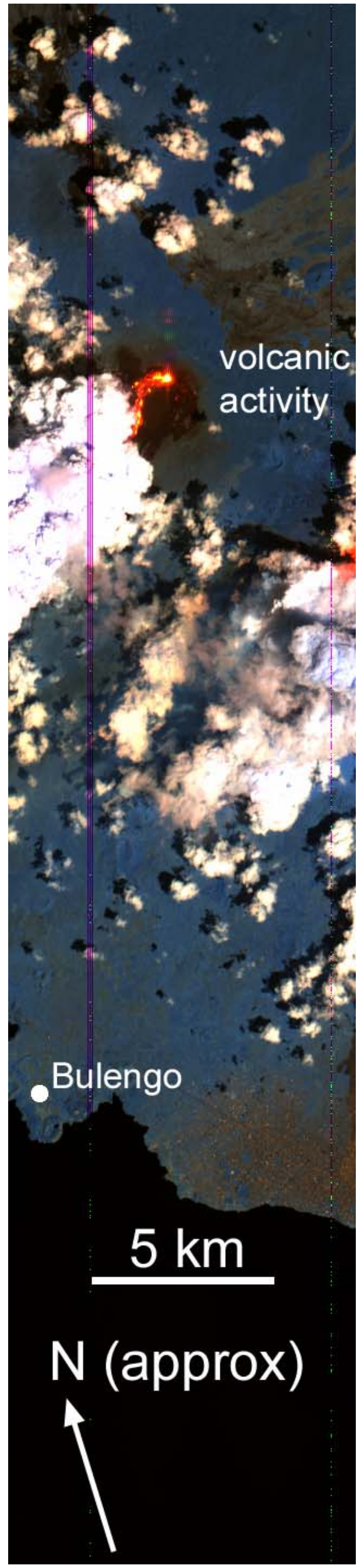


Figure 3 (right). Nyamulagira observation EO1A1730612006338110KF obtained on 4 December 2006 by the *EO-1* Advanced Land Imager (ALI). The active vent and flows (yellow and red) show up best in the short wavelength infrared bands. Image resolution is 30 m per pixel. The image is constructed from three bands as follows: red channel = 2.08-2.35 µm; green channel = 1.55-1.75 µm; blue channel = 1.2-1.3 µm. The cloud-free coast line allowed accurate positioning of the vent and lava flows manually. The ability (since May 2007) to geo-rectify data at JPL within ~24-36 hours of acquisition will aid rapid automatic generation and distribution of such products.

retasked to obtain an observation of Nyamuragira at the next available opportunity on **4 December 2006**. Subsequently, the observation was obtained, and the data processed onboard by ASE. The thermal classifier detected hot pixels, and *EO-1* was retasked to obtain another observation on 7 December 2006. Within two hours of data acquisition, the THERMAL_SUMMMARY product 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. Within 24 hours the full dataset had been downlinked and transmitted to JPL (Figure 2). On **5 December 2006** images of the volcano, showing the active vent and recently emplaced flows (Figure 3), were sent to GVO and scientists in France and Italy. These data were used to pinpoint the location of the vent and direction of flows, relocating the estimated vent position by about 2 km. This information was used by Paolo Papale and colleagues at INGV (Italy) to model likely flow direction and extent in order to determine risk to local towns.

Subsequently, steps have been taken to fully-automate the entire process. This includes setting up a website where alerts from GVO can be posted, and creating a software agent to detect these alerts. JPL now can process *EO-1* Hyperion and ALI data to Level 1G. These are data that are geo-rectified. The final steps, currently being implemented, will (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. Model-Driven Operations

Additionally, we are developing 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 Mount Erebus, and also Kilauea, in order to determine thresholds delineating unusual levels of activity. This will enable 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. This could simply be 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 possible magnitude of an eruption episode, volume erupted and even possibly the duration of the event.

## VII. 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 in a combined ground and flight 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 the *EO-1* spacecraft).

In this effort, this capability will be generalized in several ways. First, the triggering events will be generalized to enable triggers based on deeper models of the science phenomena (e.g. parameters of the physics–based model). This corresponds to triggers such as effusion estimates, changes in the modes of eruption. Additionally, we will add the capability to respond with additional data based on classes of sensor data. This corresponds to a scenario where a specific thermal measurement might be requested, with SensorML specifications being interpreted to assess available sensors and retask appropriately. Second, 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. Third, 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, duration, of a single observation or sustained measurement) but in later years we hope to extend this to enable specification of preferences over a sequence of observations (e.g. a campaign with regular intervals). Each of these technology advances will be demonstrated in the context of the volcano sensor web testbed which will link together space assets (*EO-1*, MODVOLC) with ground assets (MEVO). Such an approach can be incorporated to other Earth science disciplines. We are incorporating flood and cryosphere models and new sources of data to augment the existing Flood and Cryosphere Sensor Webs at JPL (Chien *et al.,* 2005a).

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