Rapid Response to Volcanic Eruptions with an Autonomous Sensor Web: The Nyamulagira Eruption of 2006

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Abstract—Rapid response to alerts of impending or active volcanism is vital in the assessment of volcanic risk and hazard. The JPL Model-Driven Volcano Sensor Web (MSW) demonstrated such an autonomous response during a volcanic crisis at Nyamulagira volcano, D. R. Congo, in December 2006, quickly providing vital information to volcanologists in the field. The MSW was developed to enable fast science-driven asset command and control. Alerts of volcanic activity from around the world are used to trigger high resolution observations (both spectral and spatial) by the *EO-1* spacecraft. Data are processed onboard *EO-1* by advanced software (the Autonomous Sciencecraft Experiment [ASE]). If volcanic thermal emission is detected, ASE retasks *EO-1* to obtain more data. A summary of the observation is returned within two hours of data acquisition. T[12]

TABLE OF CONTENTS

1. INTRODUCTION

IN A volcanic crisis, time is of the essence. Volcanic products, both on the ground (lava flows, pyroclastic flows, debris avalanches and lahars) and in the atmosphere (large plumes of volcanic ash) can pose serious threats to life and property both on the ground and in the air. Volcanic hazard 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 monitor and assess volcanic hazards and risks. In both cases, remote sensing of volcanoes from space-based platforms often provides the first indication that magma has reached the surface, and an eruption is in process. At NASA's Jet Propulsion Laboratory we have developed 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 management of large numbers of ground-based, atmospheric and orbiting assets need to be coordinated to minimize resource use and maximize science return.

2. MODEL-DRIVEN VOLCANO SENSOR WEB

The Volcano Sensor Web (VSW) at JPL has been described by Chien *et al.* (2005a) and Davies *et al.* (2006a, 2007). 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, managed out of NASA's Goddard Space Flight Center. Alerts come from autonomous systems processing other 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 data processing applications onboard *EO-1* (i.e., ASE, described below).

The new model-based volcano sensor web (MSW) (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, such as volcanoes with long-lived lava lakes (Erta 'Ale [Ethiopia], Erebus [Antarctica]).

The goal of the MSW is to have asset operations based on determining what additional information and data are needed to understand the state of a volcanic eruption. The required information flow between sensor web assets is performed through web services. The web service interfaces are defined by the Open Geospatial Consortium (OGC) Sensor Web Enablement (SWE) (e.g., Botts *et al.*, 2006) and allow for describing a process flow, enabling extraction of higher-level information from datasets, exchanging of metadata, determining the quality of data, acquiring instrument and data information, communicating between sensors, and 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) 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) data processing capability based on the SWE interface 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 Erebus volcano, Ross Island, Antarctica.

3. REMOTE SENSING OF VOLCANIC ACTIVITY

Both the original VSW and the new 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 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 20th Century and early years of the 21st, 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. For example, direct broadcast of satellite imaging data 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.

Model-driven Sensor Web

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│  Science studies,       │          │ Sensor Web event        │
│  research,              │          │ detection               │
│  and data analyses      │          │                         │
└─────────────────────────┘          └─────────────────────────┘
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┌─────────────────────────┐          ┌─────────────────────────┐
│  Models of              │          │  Autonomous planner     │
│  volcanic processes     │          │                         │
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┌─────────────────────────┐          ┌─────────────────────────┐
│  Model input            │          │ Search for required     │
│  requirements define    │          │ data or                 │
│  needed observations    │          │ request for data        │
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│  Scientist specifies    │          │  Spacecraft             │
│  campaigns              │          │  observations           │
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                                     │ Automatic data          │
                                     │ processing:             │
                                     │ physical parameters,    │
                                     │ product generation      │
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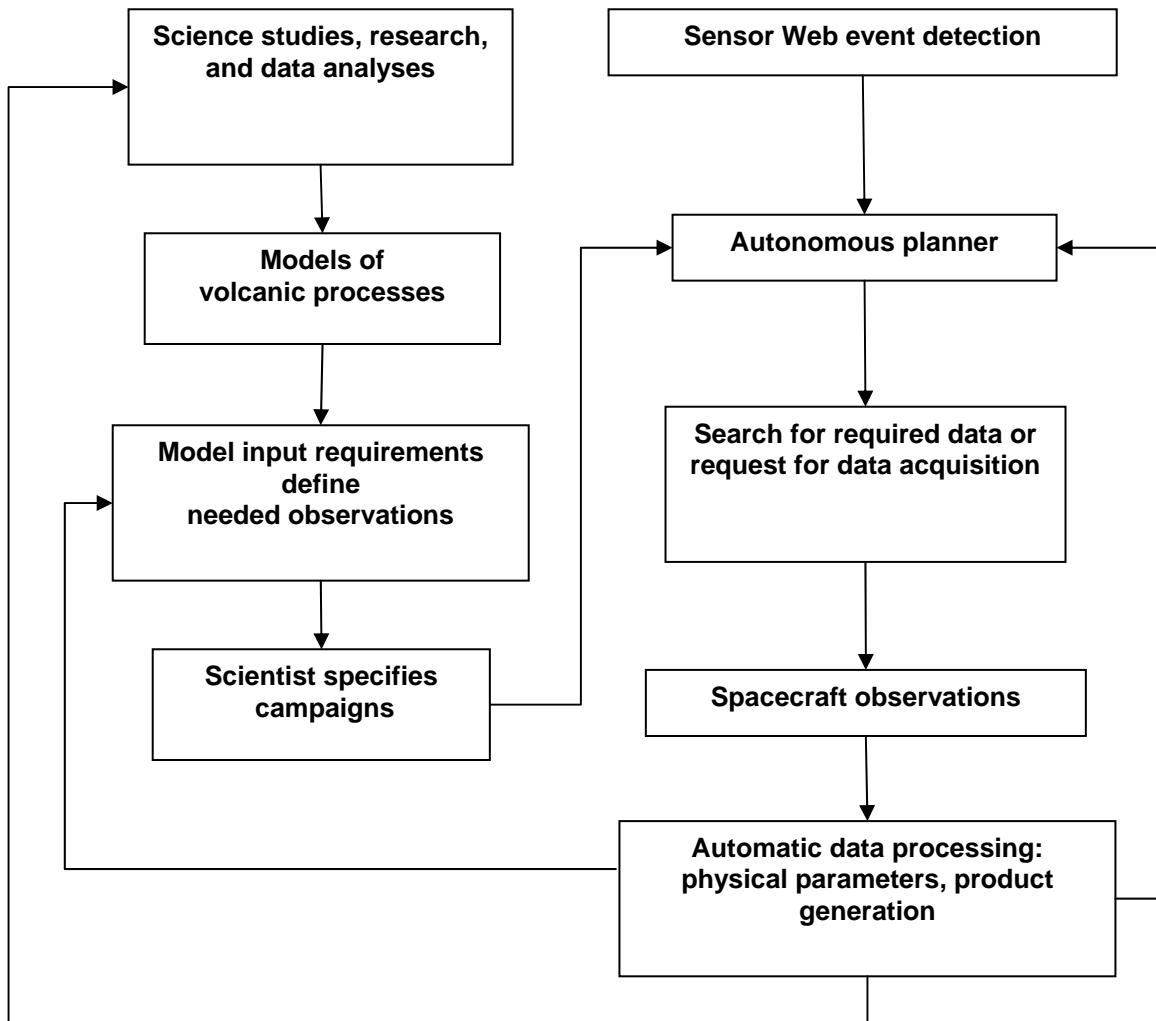
Figure 1. Layout of the Model-driven Volcano Sensor Web. An alert of volcanic activity drives a request for data to be input into models of volcanic processes to gain a better understanding of the event taking place. Data are searched for: if not available, then assets are retasked to obtain the data. 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 (Davies *et al.*, 2007).

Two such detection systems are at the University of Hawai'i. MODVOLC (Wright *et al.*, 2004) processes daily MODIS data. GOESvolc (Harris *et al.*, 2000) processes GOES (Geostationary Operational Environmental Satellite) data from the Pacific Rim at lower spatial but higher temporal (15-minute), resolution than MODIS. 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.

4. ONBOARD DATA PROCESSING AND ASE

Notification of the detection of high-temperature anomalies on the surface can be greatly increased by placing data analysis software onboard space-based platforms. 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 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 product, no larger than 20 KB in size, is downlinked with spacecraft engineering 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 of the precise timing of the spacecraft observation at time of contact, generally all that can be said is that a thermal source has been detected. This is sufficient to issue a "detection successful" bulletin. The resulting 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, funded by the NASA Advanced Information Science Technology (AIST) Program, and with the invaluable help of the USGS EROS Data Center and NASA 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.

5. 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 (also known as Nyamuragira) located at latitude 1.41 S, longitude 29.2 E, in the Democratic Republic of Congo, Africa. Nyamulagira (Figures 2, 3) is a massive, broad basaltic shield 3058 m high of some 550 km^3 in volume.

Figure 2. The Mikombe cone eruption of Nyamulagira volcano, D. R. Congo (Sept 1993). The cone reached a height of ~70 m (GVN). Image credit: Minoru Kasahara.

Figure 3. The summit of Nyamulagira is truncated by this small 2 x 2.3 km caldera with walls up to about 100 m high. Extensive lava flows emanate from the summit and from the flanks of the volcano. Ikonos image courtesy of GeoEye.
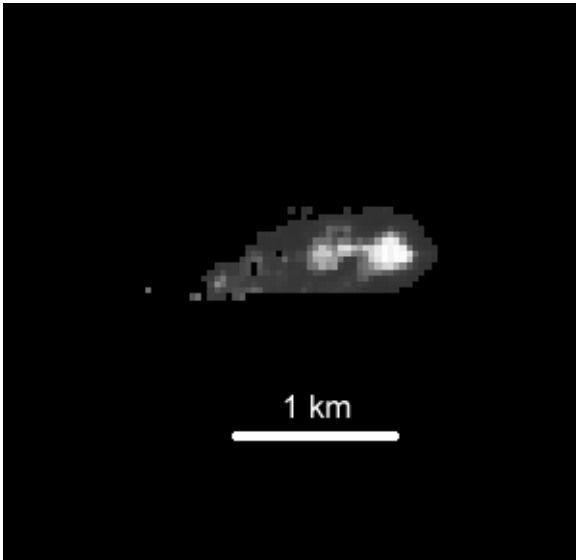
Figure 4 (above). Nyamulagira in eruption in late 2006. The eruption was detected by the ASE Thermal Classifier (Davies *et al.* 2006b), used to process *EO-1* Hyperion observation EO1H1730612006338110KF obtained on 4 December 2006. Image resolution is 30 m per pixel. The most intense group of pixels (white) denotes the active vent, where lava first reaches the surface. Lava flows move to the west (from right to left) and southwest. 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 5 (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 shore line of Lake Kivu 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.
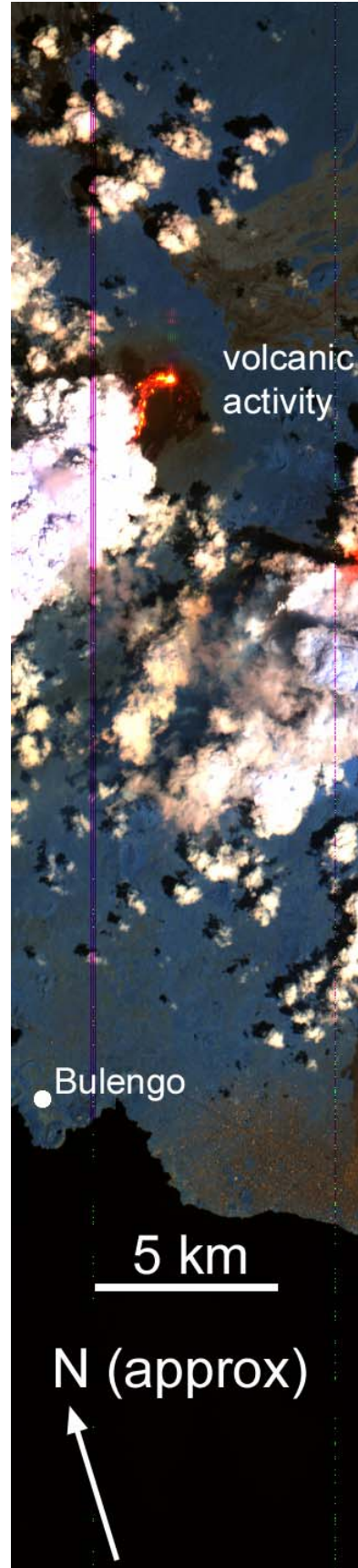
It is located in the East African Rift Valley some 25 km north of Lake Kivu and 30 km from the town of Goma (population 500 000). Africa's most active volcano, Nyamulagira is highly destructive, having erupted over 30 times since 1882. Recent eruptions have taken place every one to two years (Smithsonian Global Volcano Network [GVN]) (Figures 4 and 5). Flows from the volcano cover 1500 km^2 of the East Africa Rift Valley. Historical eruptions have occurred within the summit caldera (Figure 3), as well as from numerous fissures and cinder cones on the volcano's flanks (Figure 2). Historical flows, some voluminous and fast-moving, have extended down the flanks as far as 30 km, and have reached Lake Kivu on several occasions. The onset of most Nyamulagira eruptions is characterized by violent Hawaiian-style lava fountains that can reach several hundred meters in height and produce copious amounts of tephra and associated magmatic gases. The volcanic products extend for hundreds of kilometers downwind, causing extensive crop damage and nuisances.
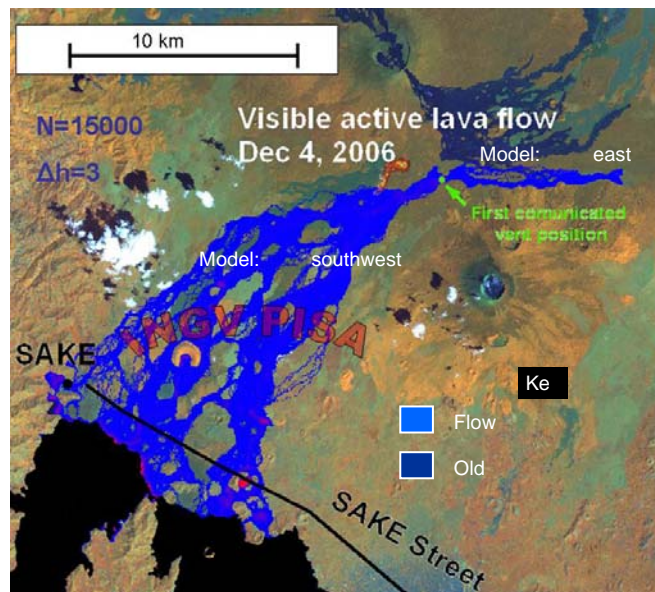
Figure 6. Model predictions of flow emplacement produced by Pablo Papale and colleagues at INGV (Italy): The light blue areas show the lava flow prediction model output, showing where flows were most likely to go, based on topography and assuming a large, voluminous eruption. The main flow field (light blue) is emplaced to the south west, but also note the flow field emplaced to the east. Image credit: INGV, Pisa, Italy.

During late October and November 2006 increased seismic activity, recorded at the Goma Volcano Observatory (GVO) of the Centre de Recherches en Sciences Naturelles (CRSN), indicated an eruption was imminent (M. Kasereka, pers. comm., 2006). Magma reached the surface on **27 November 2006**, when lava erupted on the southeastern 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). The insecurity of the region due to ongoing armed conflicts prevented volcanologists from GVO from reaching the eruption site and pin-pointing vent location. Helicopter observations were likewise very difficult and also partly impossible due to the very large amounts of tephra and gases in the atmosphere near the vent. On **1 December 2006** an urgent call went out by email for satellite imagery to help understand the dynamics of the eruption. A copy of this email reached JPL on **2 December 2006**. The *EO-1* ground software provides for an operator to identify and insert an observation into the spacecraft operations time line on short notice. 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 VSW had already triggered an observation request. 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 retasked to obtain an observation of Nyamulagira 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.
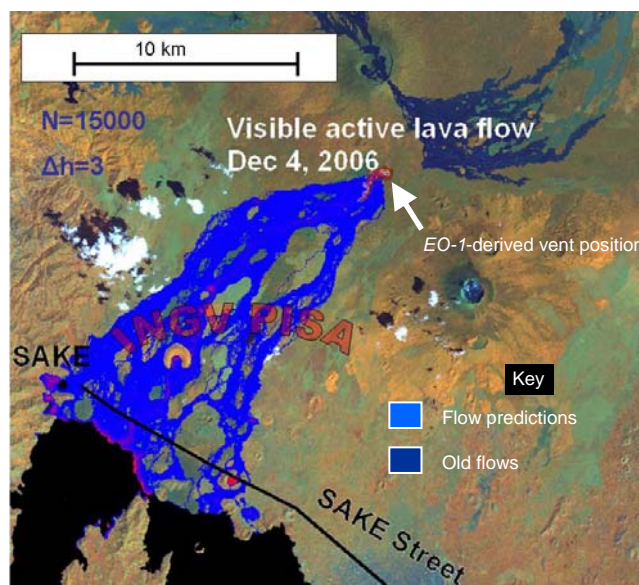

Figure 7. Model output from INGV using the accurate location of the vent derived from Hyperion data. No new flows are seen to the east. More flows are seen to the southwest. These flows have a greater potential for reaching Sake. In the end, the flows from this eruption did not reach this far. Image credit: INGV, Pisa, Italy.

Within two hours of data acquisition, the THERMAL_SUMMMARY product was available at JPL for study (Figure 4). 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. On **5 December 2006** images of the volcano, showing the active vent and recently emplaced flows (Figure 5), were sent to GVO and scientists in France and Italy. These images were used to pinpoint the location of the vent and direction of flows. The main vent was identified and was found to be some 2 km from the first estimated position. This information was used by Paolo Papale and colleagues at L'Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Italy to model likely flow direction and extent in order to determine risk to local towns. As can be seen in Figures 6 and 7, flow modeling with the new vent location revealed that no flows were likely to be emplaced to the east of the vent (Figure 6). Instead, all lava flows were emplaced to the west and southwest with a greater probability of these flows reaching the town of Sake (Figure 7), crossing the only major paved road in the region. This vital road runs along the northern shores of Lake Kivu and links the city of Goma in the eastern part of the D.R. Congo to its neighbour, Gisenyi, in Rwanda, and to the town of Sake and the rest of the D. R. Congo. Such information allowed volcanologists at GVO to assess hazard and direct resources accordingly.

The eruption of Nyamulagira in November-December 2006 was, thankfully, brief. Flows from this event did not reach any villages or towns nor cross the paved road, unlike previous eruptions from Nyamulagira and the nearby volcano Nyiragongo (in 2002, drainage of the lava lake triggered a flank eruption from Nyiragongo sent broad, fast-moving flows over a distance of 19 km through the city of Goma into Lake Kivu. There was great loss of life and property (Komorowski *et al.*, 2004). Nevertheless, the value of the autonomous sensor web was effectively demonstrated during the 2006 Nyamulagira eruption.

6. OTHER EXAMPLES: MANDA HARARO

In August and September 2007, other east African volcanoes were imaged as a result of Sensor Web operations. The first was Manda Hararo (long. 40.82 E, lat. 12.170 N) in the Afar region of Ethiopia. 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.

7. OTHER EXAMPLES: OLDOINYO LENGAI

On August 29 2007 the volcano Oldoinyo Lengai (long. 35.902 E, lat. 2.751 S), in the East African rift Valley in Tanzania, was imaged by *EO-1*. The observation resulted from another thermal detection by MODVOLC. Oldoinyo

Lengai (Figure 8) 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, some hundreds of degrees less than that of basalt lava (typically 1150 ºC).

Figure 8. Oldoinyo Lengai, Tanzania, erupting in 1966 (Image credit: GVN).

It was not known if an eruption could be detected by ASE, as Hyperion was not particular sensitive to this lower-temperature volcanism. Although a number of day and nighttime observations had been obtained from 2004 to 2007, no thermal detection had been made. 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 from the crater to the northwest. 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.

8. SENSOR WEB GOALS FOR 2007

Subsequent to the success of the VSW with Nyamulagira, steps have been taken to fully-automate data processing, analysis and product generation. At time of writing, GVO is developing a system to publish alerts to the Internet. The second step is to create a software agent used by the VSW to detect these alerts. The final step is automating posting of the acquired products and analysis to the scientists.

Our goals for the remainder of 2007 (Figure 9) include the automatic generation of image "products" (true-color and false-color images created from data at visible and infrared wavelengths) that clearly show the location of volcanic activity (see Figure 5). These are relatively simple products to generate, but are probably of greatest value to volcanologists who are concerned with where lava is erupting from and where it is going. As part of AIST-funded work, data from Hyperion are processed to yield locations that initial analyses suggest are within +/- 300 m

along track and +/-200 m across track. The process of plotting hot pixels on a map or grid is currently being implemented. By the end of 2007, for each observation obtained by the Sensor Web, hot spot locations will be plotted, estimates of thermal emission and effusion rate generated, images produced and transmitted to interested parties within a few hours of data acquisition. Already, the full Hyperion (and ALI) datasets are generally available for additional processing within 48 hours of acquisition. Just two years ago, receipt of radiometrically corrected data took some two to three weeks.
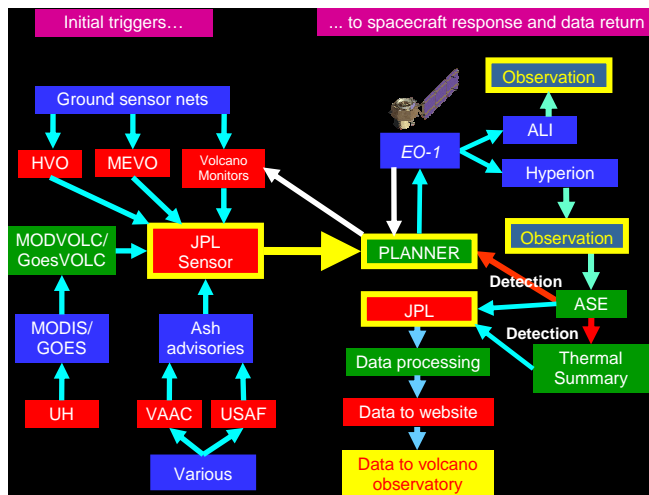
Figure 9. The Volcano Sensor Web at the end of 2007, including two-way triggering between spacecraft and *in situ* sensors.

9. TWO-WAY SENSOR WEB OPERATIONS

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 being demonstrated by the installation of two sensor packages on Kilauea volcano, Hawai'i, in November 2007 (Boudreau *et al.*, 2007), which are connected to *EO-1* via the VSW. In this demonstration project, SO_2 sensors have been incorporated into expendable "Volcano Monitor" capsules to be placed downwind of the Pu'u 'O'o vent of Kilauea volcano, Hawai'i (Boudreau *et al.*, 2007). In nominal (low) power conservation mode, data from these sensors are collected

and transmitted every hour to the Volcano Sensor Web through the Iridium Satellite Network. If SO_2 readings exceed a predetermined threshold, the modem within the Volcano Monitor sends an alert to the JPL Sensor Web, triggering a request for prompt *EO-1* (Hyperion) data acquisition (Boudreau *et al.*, 2007) and increasing the data acquisition rate at the *in situ* sensor. During pre-defined "critical events" as perceived by multiple sensors (which could include both *in situ* and spaceborne devices), the Sensor Web can order the SO_2 sensors within the Volcano Monitor to increase 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).

10. 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 Erebus volcano, Antarctica, and Kilauea volcano, Hawai'i, 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.

11. 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 SWE 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.

12. OTHER SENSOR WEB ACTIVITIES

In addition to the Volcano Sensor Web, other sensor web operations are currently operating. 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.

13. FUTURE PLANS

Future plans for the Volcano Sensor Web include (1) incorporating more data sources from other volcano observatories and data processing systems around the world; (2) incorporating algorithms that process the ASE THERMAL_SUMMARY product to yield estimates of total thermal emission and effusion rate as a systematic product; (3) systematic processing of ALI data, which covers a larger area than Hyperion (an ALI observation is 38 km wide rather than 7.7 km wide with Hyperion); and (4) the possible onboard image generation for transmission with the THERMAL_SUMMARY product to provide context to thermal detections. This product would be delivered some 24 hours before the full dataset is downlinked and processed. However, with strong constraints on the size of ASE products that can be downlinked with spacecraft telemetry (20 kb), this might not be possible with *EO-1*. Such a product would nevertheless be highly desirable on future missions.

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