ONBOARD PROCESSING OF MULTISPECTRAL AND HYPERSPECTRAL DATA OF VOLCANIC ACTIVITY FOR FUTURE EARTH-ORBITING AND PLANETARY MISSIONS

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ABSTRACT

Autonomous onboard processing of data allows rapid response to detections of dynamic, changing processes. Software that can detect volcanic eruptions from thermal emission has been used to retask the Earth Observing 1 spacecraft to obtain additional data of the eruption. Rapid transmission of these data to the ground, and the automatic processing of the data to generated images, estimates of eruption parameters and maps of thermal structure, has allowed these products to be delivered rapidly to volcanologists to aid them in assessing eruption risk and hazard. Such applications will enhance science return from future Earth-orbiting spacecraft and also from spacecraft exploring the Solar System, or beyond, which hope to image dynamic processes. Especially in the latter case, long communication times between the spacecraft and Earth exclude a rapid response to what may be a transient process – only using onboard autonomy can the spacecraft react quickly to such an event.

Index Terms— Autonomy, remote-sensing, volcanism, Earth, Jovian satellites

1. INTRODUCTION

Future space missions that monitor Earth's surface and environment will generate massive volumes of data. For example, the proposed NASA HyspIRI mission, in its current design, would generate 10^9 bits (1 gigabit, or 1.5 megapixels) per second of operation. Downlinking and processing these data in order to identify new volcanic eruptions, or changes in existing eruptions, in a timely manner to assist in the determination of volcanic risk and hazard, would be a major challenge [1]. Ideally, if data could be processed onboard the spacecraft, then the results of the analysis could be speedily downlinked and subjected to additional processing on the ground. The resulting products would be distributed to end-users, in this case, the relevant volcano observatory scientists and regional/local decision makers. Such an autonomous system (for example, the NASA New Millennium Program Autonomous Sciencecraft, described in the next section) has been successfully demonstrated.

2. THE AUTONOMOUS SCIENCECRAFT (ASE)

The Autonomous Sciencecraft (ASE) [2-4] is advanced software developed under the auspices of the NASA New Millennium Program. ASE has been flying on the *Earth Observing-1* (*EO-1*) spacecraft since mid 2004. ASE consists of an onboard planner that manages available resources, a spacecraft command language that interprets commands from the planner to operate the spacecraft and instruments, and data classifiers that process Hyperion hyperspectral imagery (196 bands from 0.4 to 2.5 μm). It is not possible to rapidly (i.e., within a few hours) downlink the entire Hyperion observation, which may exceed 200 MB in size. Instead, the results of the onboard processing, a highly-compressed précis of the science content of the observation in a small file no larger than 20 KB, is downlinked during more frequent engineering contacts, typically within 90 minutes of data acquisition. For volcano observations, this file consists of the radiant flux at 12 wavelengths for each pixel containing anomalous thermal emission [3]. These wavelength tables are carefully selected across the Hyperion wavelength range to correspond to windows of maximum transmission through the atmosphere. The daytime wavelength table includes bands suitable for producing an accurate true-colour image. Thus, the location and extent of the ongoing volcanic activity is quickly available for distribution and additional analysis. Also onboard *EO-1* is the Advanced Land Imager (ALI). This is a multispectral imager with bands across the same wavelength range as Hyperion. Data are at 30 m per pixel for all bands except for the panchromatic (PAN) band, an open filter with images at 10 m per pixel. The four swaths of ALI data per observation create a scene some 30 km wide. ALI data are collected with every Hyperion observation. Mostly as a result of improvements in communications software, operational advances have reduced the time taken for delivery and processing of the full Hyperion (and ALI) dataset from 2-3 weeks in 2003 to 24-36 hours in 2009, and to 4-6 hours in 2010. This is a great boon in allowing rapid processing and delivery of products to end-users. Ground-based processing now includes a pixel-by-pixel derivation of thermal emission, incorporating atmospheric correction, sunlight removal, correction for viewing geometry [5], and which now yield

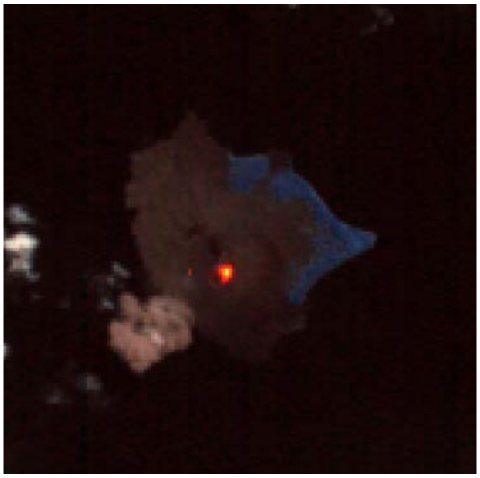
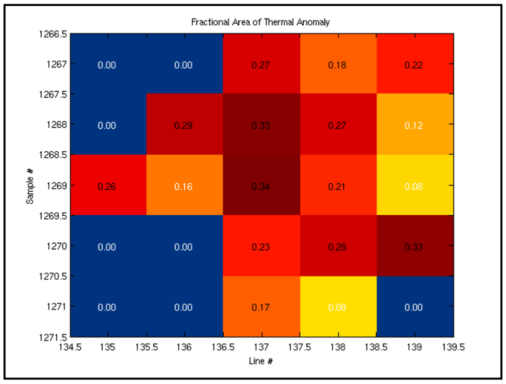


Figure 1 (above). Hyperion short wavelength infrared observation of Krakatau volcano (Indonesia) on 2009 August 23 showing an ongoing eruption in the summit crater. Spatial resolution is 30 m/pixel.

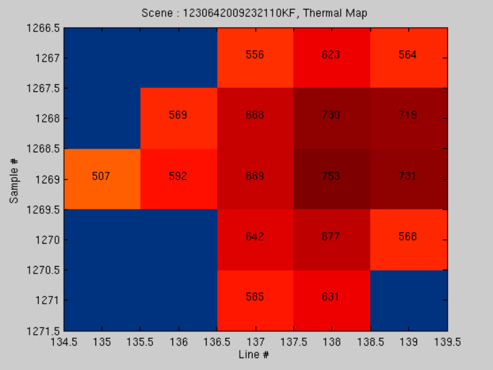
Table 1. Autonomous data processing output	
Mass Effusion rate:	**130.19 kg/s**
Volumetric Effusion rate:	**0.05 m^3/s**
Total Power loss:	**3.91e+07 W**
Radiative Power loss:	**2.86e+07 W**
Convective Power loss:	**1.05e+07 W**
Look Angle:	**6.29 (deg)**
Range to Ground:	**692.77 (km)**

radiometrically corrected and geo-located products that identify the location of ‘hot’ pixels [Figure 1], maps of thermal emission and pixel fraction occupied by the thermal source, [Figures 2, 3], and the integrated thermal emission, a quantity that can be used to estimate the eruption effusion rate [Table 1]. Additionally, the integrated thermal emission data are automatically added to any previously available data to produce a history of activity at the volcano to date, with calculations indicating if the current activity is statistically significant. These results can be used to prioritise eruption notifications and to act as a trigger for requests of additional observations not only by *EO-1* but other assets as well. The entire system is autonomous [4, 6]. The current system, based at NASA’s Jet Propulsion Laboratory, has, at best, obtained and processed onboard *EO-1* an observation from a sensor web trigger in a mere two hours (Mt. St. Helens, July 2008). This was fortuitous - the timing of the alert, the next scheduled uplink and the position of the spacecraft made this fast reaction possible. Typically, the first *EO-1* imaging of a target after receipt of an eruption or precursor notification takes 1-2 days.



Sample # \ Line #	135	136	137	138	139
1267	0.00	0.00	0.27	0.18	0.22
1268	0.00	0.29	0.33	0.27	0.12
1269	0.26	0.16	0.34	0.21	0.08
1270	0.00	0.00	0.23	0.28	0.33
1271	0.00	0.00	0.17	0.08	0.00

Figure 2. Thermal map of hot pixels identified in Figure 1 by the thermal classifier flying on *EO-1* [5].



Sample # \ Line #	135	136	137	138	139
1267			556	623	564
1268		569	668	730	719
1269	507	592	669	753	731
1270			642	677	568
1271			585	631	

Figure 3. Fraction of pixels filled by thermal sources at temperatures given in Fig. 2 [5].

3. EYJAFJALLAJÖKULL

The March-June 2010 eruption of Eyjafjallajökull, Iceland, brought chaos to air travel across Europe, and was another wake-up call to the dangers posed by explosive eruptions to general aviation. Although the eruption was small by total volume erupted, the production of fine particulates, mostly the result of explosive lava-water interaction, posed a severe threat to jet engines. The closure of most of European airspace brought travel chaos to much of the globe. Alerts issued by the London Volcanic Ash Advisory Centre [one of seven VAACs]) led to airspace closure and avoided any loss of aircraft. However, this eruption highlights the need for more links between volcano observatories and other organizations and the Volcano Sensor Web in order to obtain data close to the beginning of the eruption, rather than from alerts that the eruption was underway.

The eruption began on 20 March 2010, close to Fimmvorduhals, a pass and hiking trail between the Eyjafjallajökull and Myrdalsjökull icecaps. With no link between *in situ* sensors and the VSW, there was no automatic triggering of the sensor web. Instead, commercial news reports alerted the VSW team to the eruption, and, with the onset of the eruption taking place at a weekend, retasking *EO-1* took longer than it would have if the triggering had been autonomous, using alerts that were accessible by the system. Subsequently, of course, alerts

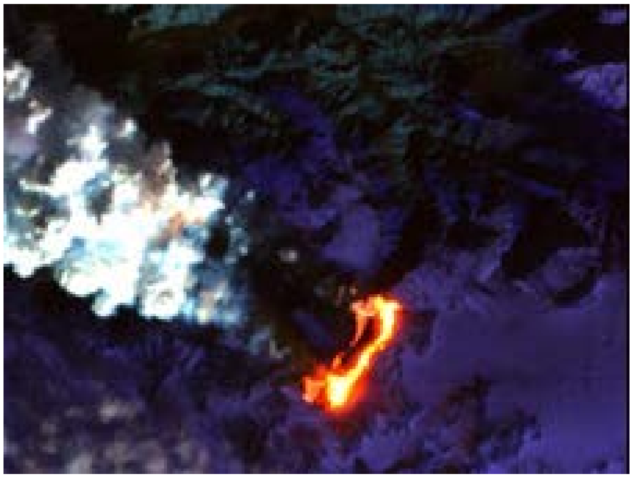


Figure 4. False-color short-wavelength infrared image of the eruption at Fimmvorduhals (Eyjafjallajökull volcano) Iceland. Data were obtained by NASA's *EO-1* Hyperion instrument on March 24, 2010. The image shows lava fountains and open channel flows. Image credit: NASA/JPL/*EO-1* Mission/GSFC/Ashley Davies.

poured into the VSW from spacebased assets (MODVOLC, at the University of Hawai'i, which processes MODIS data) and from the London VAAC. The first *EO-1* observation of the eruption at Fimmvorduhals was therefore obtained on March 24 2010 (Figure 4). Data products were transmitted to volcanologists in Iceland. Between March 24 and June 5 2010, 50 observations were obtained by *EO-1* of this eruption, with about 50% of them being of limited use due to cloud cover.

We are now working with the University of Reykjavik and Icelandic Meteorological Office and are investigating if a triggering system for the VSW can be instituted, so that notifications of precursors of likely volcanic activity may allow *EO-1* to catch the onset of activity.

4. HysPIRI

It is therefore desirable to include such a capability on future missions. The proposed HyspIRI mission in particular would benefit greatly from both an onboard processing capability and autonomous ground-processing of data. Instrumentation would consist of an imaging spectrometer measuring from the visible to short wave infrared (VSWIR) and a multispectral thermal infrared (TIR) imager. The VSWIR and TIR instruments would both have a spatial resolution of 60 m at nadir. The VSWIR would have a surface point revisit period of approximately three weeks. The TIR, with a much wider swath, would have a surface point revisit period of approximately 1 week. The broad wavelength range of the proposed HyspIRI instruments means that pre-eruption thermal anomalies might be identified at thermal infrared wavelengths. For ongoing eruptions, onboard classifiers could identify the style of volcanic activity, thus allowing the correct models of effusion to be used to quantify eruption processes. Recent analysis of terrestrial remote-sensing data identifies the following wavelength selection for best constraining temperature distribution for ongoing volcanic eruptions, including lava fountains, open-channel and insulated lava flows, active lava flows, lava domes and insulated highly-silicic lava flows [7]. Balancing a desire to return as much data as possible with constraints on product size and the available processing capability, the optimum minimum wavelength set for an onboard classifier would be 2, 5, 8, and 12 μm. Of course, data at more wavelengths is always desirable and would be supplied by proposed HyspIRI instruments. Additional constraints for fits to the thermal emission spectrum would be possible with data at 3 μm. Finally, the number of thermally-active pixels is a tiny fraction of the total number in an observation (typically of order 10 to 100, out of 1.5 M pixels collected per second). At the very least, instrument data just for these pixels could be quickly returned. This is particularly useful for night-time observations, when the thermally-active pixels are easily detected, are unadulterated by solar insolation (and are therefore easier to correct and use to quantify volcanic thermal emission), and represent most if not all of the science content of the entire observation.

5. IO AND EUROPA

The same classifier could also be used onboard a potential future mission to the volcanic jovian moon Io [7, 8] where long communication times means an onboard capacity to identify high-priority data would increase science return per returned byte, especially where there are constraints on downlink. As noted previously [8] the benefits of Artificial Intelligence and spacecraft autonomy onboard a deep-space mission can be illustrated by considering how best to detect and monitor a dynamic, unexpected event of high science interest, such as an ongoing, large-scale but short-lived volcanic eruption [9]. The jovian moon Io is intensely volcanic, and although studied extensively by the NASA *Galileo* spacecraft, many questions remain as to the precise nature of the composition of the erupting lavas, specifically, whether very-high temperature ultramafic lavas are present [10, 11]. Ultramafic lava would apply strong constraints on the thermal and chemical evolution of Io's interior [12]. The projected science objective would therefore be to determine the temperature of Io's lavas and constrain possible compositions.

Given the nature of thermal emission from active volcanism, the best opportunity for detecting high-temperature lavas comes from rare lava-fountain events, where relatively large areas at or close to magma liquidus temperatures are exposed. Even from a great distance away, even from the orbit of Europa, it is possible to determine a lower limit on magma temperature, a very strong constraint on composition. For *Galileo*, engaged in multiple fly-bys of the Galilean satellites, each encounter observation sequence was planned well in advance. Instrument setting and exposure times were pre-ordained. Although lava fountains were observed, in one case at high spatial resolution, observations were planned to image the non-thermally active background and the intense thermal emission saturated both the visible imaging system (SSI) and infrared imager (NIMS). There was no opportunity to quantify the intensity of the thermal emission and change observation sequencing and instrument settings. By the time data had been returned to Earth and analysed, the spacecraft had moved on and the science event was over.

An onboard AI would do things very differently. Onboard data processing would quickly identify an intense thermal source at a great distance, calculate the opportune moment to make observations (with visible and infrared imagers in the 0.4 to 15 micron range to capture the full thermal emission spectrum), and set the appropriate instrument gain state or exposure time to obtain unsaturated data. Additional instrumentation could be brought to bear on the new eruption: an ultraviolet spectrometer would be used to study erupting gas. Subsequent orbits would flag this location for in-depth visible and infrared study to determine composition spectroscopically.

The science content of the returned data would therefore be increased from an acquisition queue using preset observation sequencing, the need for communications (data transfer and commands, and accompanying time lag) between spacecraft and Earth for spacecraft re-tasking would be eliminated, the use of bandwidth would be optimised, and an important science question could be answered by making decisions on the spot. A mission to Europa, such as the NASA Jupiter Europa Orbiter Flagship mission now under study, would spend at least two years in the Jovian system. This would allow considerable lengths of time for monitoring Io.

Detection of active resurfacing processes on Europa would be a major discovery. Such detections are best accomplished by either detecting plumes or by detecting anomalous thermal signatures on the surface in the thermal infrared [13]. Data classifiers based on the cryosphere and thermal detectors on ASE would fly on the proposed Europa Mission, processing hyperspectral data and data from other instruments to detect such spectral features [13], a low-cost process with a potential huge science return.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] Chien, S., D. Silverman, A. G. Davies and D. Mandl, 2009, Onboard science processing concepts for the HyspIRI mission, *IEEE Intelligent Systems*, 24, no. 6, 12-19.

[2] Chien, S., R. Sherwood, D. Tran, B. Cichy et al., 2005, Using Autonomy Flight Software to Improve Science Return on Earth Observing One, *Journal of Aeropace Computing, Information, & Communication*, 2005, AIAA, 2, 196-216.

[3] Davies, A. G., S. Chien, V. Baker, T. Doggett, et al., 2006, Monitoring Active Volcanism with the Autonomous Sciencecraft Experiment on EO-1, *Rem. Sens. Environ*., 101, no. 4, 427-446.

[4] Chien, S., B. Cichy, A. G. Davies, D. Tran, et al., 2005, An Autonomous Earth-Observing Sensorweb, *IEEE Intelligent Systems*, 20, no. 3, 16-24.

[5] Davies, A. G., J. Calkins, L. Scharenbroich, R. G. Vaughan, et al., 2008, Multi-Instrument Remote and In Situ Observations of the Erebus Volcano (Antarctica) Lava Lake in 2005: a Comparison with the Pele Lava Lake on the Jovian Moon Io, *J. Volc. Geotherm. Res.,* 177, vol. 3, 705-724, and online electronic supplement.

[6] Davies, A. G., S. Chien, R. Wright, A. Miklius, P. R. Kyle, M. Welsh, J. B. Johnson, D. Tran, S. R. Schaffer, and R. Sherwood, 2006, Sensor web enables rapid response to volcanic activity, *Eos*, 87 (1), 1&5.

[7] Davies, A. G., L. Keszthelyi and A. J. L. Harris, 2010, The Thermal Signature of Volcanic Eruptions on Io and Earth, *JVGR*, in press. doi:10.1016/j.jvolgeores.2010.04.009.

[8] Davies, A. G., S. Chien, T. Doggett, F. Ip and R. Castaño (2006) Improving Mission Survivability and Science Return with Onboard Autonomy, *Proc. International Planetary Probe Workshop-4*, Pasadena, CA, USA, June 27-30, 2006.

[9] Davies, A. G., Increasing deep-space mission science return through onboard identification of dynamic events: examples from planetary volcanology, *Eos Trans. AGU, 87(36), Jt. Assem. Suppl.,* Abstract IN43E-02, 2006.

[10] McEwen A. S. *et al.*, High-Temperature Silicate Volcanism on Jupiter's Moon Io, *Science*, 281, 87, 1998.

[11] Davies, A. G., *et al.*, Thermal signature, eruption style and eruption evolution at Pele and Pillan on Io *J. Geophys. Res.*, 106, E12, 33,079-33,104, 2001.

[12] Keszthelyi, L. P. *et al.* A post-*Galileo* view of Io's interior, *Icarus*, 169, 271-286, 2004.

[13] Doggett, T. C., A. G. Davies and R. Greeley, Detectability of cryo-volcanism with thermal infrared spectroscopy, *Lunar. Plan. Sci. Conf. XXXVII* abstract 2243, on CD-ROM, 2006.