MAXIMIZING MISSION SCIENCE RETURN THROUGH USE OF SPACECRAFT AUTONOMY: ACTIVE VOLCANISM AND THE AUTONOMOUS SCIENCECRAFT EXPERIMENT.

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Introduction: Until now, deep-space missions were unable to react to dynamic events as observation sequences were planned in advance. In the case of planet, asteroid and comet fly-bys, the limited resources available are allocated to individual instruments long beforehand. However, for monitoring or mapping mission phases, alternative strategies and technologies are now available. Now, onboard data processing allows greater spacecraft and instrument flexibility, affording the ability to react rapidly to dynamic events, and increasing the science content of returned data. Such new technology has already been successfully demonstrated in the form of the Autonomous Sciencecraft Experiment (ASE) [1-3].

The Autonomous Sciencecraft Experiment: In 2004 the New Millennium Program (NMP) Autonomous Sciencecraft Experiment (ASE) successfully demonstrated advanced autonomous science data acquisition, processing, and product downlink prioritization, as well as autonomous fault detection and spacecraft command and control.

ASE is software onboard the EO-1 spacecraft, in Earth-orbit. ASE controlled the *Hyperion* instrument, a hyperspectral imager with 226 wavelengths from 0.4 to 2.4 µm and 30 m/pixel spatial resolution.

ASE demonstrated that spacecraft autonomy will be advantageous to future missions by (a) making the best use of limited downlink, e.g., by increasing science content per byte of returned data, and by avoiding the return of null (no-change/no feature) datasets (see *Volcano Observations*); and (b) overcoming communication delays through decision-making onboard enabling fast reaction to dynamic events.

ASE Science Algorithms: ASE science classifiers [4-6] used onboard ASE during 2004 (and into 2005) consisted of the following:

Thermal Classifier: Detection of pixels with a strong thermal component, characterized in most cases with an increase in thermal emission towards longer wavelengths. The classifier is used to detect volcanic thermal emission, and is applied to both day and (preferably) night-time observations [4].

Cryosphere Classifier: Classifies surface as snow, water, ice or land; is used to monitor formation and retreat of sea and lake ice; and separates water/ice from land for sub-classification of land type [5].

Floodwater classifiers: monitor river systems for change in total area covered by water, even sediment-laden floodwater. Used mainly for detecting and monitoring annual/seasonal flooding events [6].

Cloud detection: The cloud detection algorithm [5] is used to identify the extent of cloud cover before applying other classifiers. For example, observations with more than 50% cloud cover can be discarded. ASE can then schedule a follow-up observation.

Stacking of algorithms: ASE science classifiers can be run in sequence, e.g., the cloud classifier can be run if no thermal detection is made in a daytime scene to determine if the non-detection may be due to cloud cover, rather than an absence of volcanic activity.

Volcano Observations: In May 2004 ASE was successfully tested on Mt. Erebus, Antarctica, a volcano with an active lava lake at its summit. Controlled by ASE, Hyperion obtained an observation of Erebus and processed the data onboard into a product suitable for analysis with the Thermal Classifier [4]. The thermal detector uses a combination of ratios and thresholds of data at 1.25, 1.65, 2.25 and 2.28 µm. The thermal classifier was run on the data product and detected thermal emission from the lava lake. The following actions were then autonomously taken:

1. The onboard planner retasked EO-1 to observe Erebus again at the next available opportunity.
2. A routine Stromboli observation was removed from the planned observation list as a result of action 1.
3. A thumbnail of the classifier output was created and, with a summary of the classifier output (number of hot pixels), was downlinked with spacecraft telemetry.
4. Seven hours after the first observation, the repeat observation, scheduled in action 1, was obtained. This also showed thermal emission from Mt. Erebus.

The important points to note are, firstly, the identification of active volcanism was on the ground and in the hands of scientists two hours after initial data acquisition and, secondly, the spacecraft obtained a follow-up observation rapidly without human intervention. Erebus was chosen for the initial test because it was a steady thermal source, but ASE has subsequently demonstrated increased flexibility of spacecraft operations on other targets. Under ASE control

EO-1 has obtained over 100 observations of many volcanoes during 2004, including Mt St Helens (lava dome), Kilauea, HI (pahoehoe flow fields), Erta Ale, Ethiopia (lava lake), and Etna, Sicily (channeled flows).

Increased science return: Given limited resources, ASE demonstrated increased science return in a number of ways: for example, with data editing. From the large hyperspectral dataset (which can be >500 Mb in size) a data subset containing the feature of interest can be extracted. In the case of volcano monitoring, 10 wavelengths (out of 226) useful for quantifying the eruption are rapidly returned with spacecraft telemetry ahead of the slower process of downlinking the full dataset. These datasets are ~20Kb in size, yet the science content of the original dataset is preserved. Volume of data return can be squeezed even more through return of just the number of hot pixels detected. The ultimate resource saving is made by not returning a null observation: if a night-time *Hyperion* scene is obtained and no thermal emission is detected then there is no need to return these data, thus saving downlink for more valuable observations.

Finally, there will be times when return of all data collected will be impossible due to limited downlink. In this event a précis of the data (as described above) can be returned for those events detected by onboard science algorithms. This is a vast improvement on no data return at all from these observations.

Rapid notification of dynamic event: The small datasets described above are suitable for eruption notification purposes. These, at least, allow the decision to be made (either manually or autonomously) to further investigate the detection. Relevant parties are (autonomously) alerted by email, and assets can be mobilised.

Increase temporal coverage of observations: The detection of a dynamic volcanic event autonomously triggers retasking of EO-1 and can trigger the aquisition of additional observations with a higher-resolution instrument (the ALI camera on EO-1 has a panchromatic band with 10 m/pixel resolution). Other assets can be alerted as well to maximize coverage. Once triggered, observations can be ‘daisy-chained’ together with subsequent observations being triggered by detections. A series of observations of the 2004 Mt St Helens eruption was obtained in this way. Temporal coverage of an eruption thus increases from a nadir observation every 16 days to a maximum of 10 (5 day, 5 night) in 16 days.

Impact on exploration: Terrestrially and extra-terrestrially this new, proven technology affords a rapid response to dynamic events: on Earth, detection of volcanic eruptions and floods can be rapidly passed to the the relevant authorities; on Mars, for example, surface assets can be used to pass detections of weather systems and atmospheric phenomena to orbital assets to catch dynamic events, while orbital assets can warn surface assets of adverse weather conditions approaching. As demonstrated with Mars Odyssey THEMIS data [7], a compressed data stream can be monitored for a specific spectral feature which is then used to track the edge of the ice cap as it changes seasonally.

Future uses of ASE:- planetary volcanism:

Mission example 1: Io volcanism. The volcanic moon Io can be observed from missions such as the Jupiter Icy Moons Orbiter. Between icy satellite orbital mission phases there will be numerous opportunities to monitor volcanism on Io on different time scales (minutes-weeks, or longer). As on Earth, the largest volcanic eruptions on Io are the rarest, and the phase of most intense activity is short. Monitoring data with ASE applications allows rapid detection of such an event. ASE would re-target other instruments, re-scheduling lower-priority observations. Most importantly, if sensors become saturated, ASE allows for rapid gain and/or exposure adjustment to avoid saturation, greatly increasing the scientific value of the data thus obtained.

Mission examples 2: Cryo-volcanism. Missions to icy satellites can use ASE thermal classifiers to search compressed datastreams for spectral features consistent with thermal emission from cryovolcanic processes.

Mission example 3: Volcanism on Mars. Mars remote-sensing data (e.g., MRO) can be scanned to search for active volcanism. For minimal use of resources, the opportunity exists for reaction to discovery without delays imposed by Earth communications.

Summary: ASE has successfully demonstrated that a spacecraft can be driven by science analysis and autonomously controlled. ASE is available for flight on other missions. Mission hardware design should consider ASE requirements for available onboard data storage, onboard memory size and processor speed.

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