

# Enhancing Science and Automating Operations using Onboard Autonomy

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Autonomy software, as part of the NASA New Millennium Space Technology 6 Project, is currently flying onboard the Earth Observing One (EO-1) Spacecraft. This software enables the spacecraft to autonomously detect, track, and respond to science events observed in instrument data. Included are onboard software systems that perform science data analysis, deliberative planning, and run-time robust execution. This software has demonstrated the potential for space missions to use onboard decision-making to detect, analyze, and respond to science events, and to downlink only the highest value science data. Using this science agent, the EO-1 mission has experienced over 100 times increase in science return measured as the number of science events captured per megabyte of downlink. As a result, significant portions of the mission planning & sequencing processes have been automated, reducing EO-1 operations cost by \$1M/year. In this paper, we will describe the evolution of the software from prototype to full time operation onboard EO-1. We will quantify the increase in science, decrease in operations cost, and streamlining of operations procedures. Included will be a description of how this software was adapted post-launch to the EO-1 mission, which had very limited computing resources which constrained the autonomy flight software. We will discuss ongoing deployments of this software to the Mars Exploration Rovers and Mars Odyssey Missions as well as a discussion of lessons learned during this project. Finally, we will discuss how the onboard autonomy has been used in conjunction with other satellites and ground sensors to form an autonomous sensor-web to study volcanoes, floods, sea-ice topography, and wild fires. As demonstrated on EO-1, onboard autonomy is a revolutionary advance that will change the operations approach on future NASA missions. The importance of this software has been recognized by numerous awards including being a co-winner of the 2005 NASA Software of the Year Award.

## Nomenclature

ALI	=	Advanced Land Imager
ASE	=	Autonomous Sciencecraft Experiment
CASPER	=	Continuous Activity Scheduling Planning Execution and Replanning software
EO-1	=	Earth Observing One
SCL	=	Spacecraft Command Language

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## I. Introduction

SINCE January 2004, the Autonomous Sciencecraft Experiment (ASE) running on the EO-1 spacecraft has demonstrated several integrated autonomy technologies to enable autonomous science. Several science algorithms including: onboard event detection, feature detection, and change detection are being used to analyze science data. These algorithms are used to downlink science data only on change, and detect features of scientific interest such as volcanic eruptions, growth and retreat of ice caps, flooding events, and cloud detection. These onboard science algorithms are inputs to onboard planning software that can modify the spacecraft observation plan to capture high value science events. This new observation plan is then executed by a robust goal and task oriented execution system, able to adjust the plan to succeed despite run-time anomalies and uncertainties. Together these technologies enable autonomous goal-directed exploration and data acquisition to maximize science return. This paper describes the specifics of the ASE and relates it to past and future flights to validate and mature this technology.

The ASE onboard flight software includes several autonomy software components:

- Onboard science algorithms that analyze the image data to detect trigger conditions such as science events, “interesting” features, changes relative to previous observations, and cloud detection for onboard image masking
- Robust execution management software using the Spacecraft Command Language (SCL)<sup>1</sup> package to enable event-driven processing and low-level autonomy
- The Continuous Activity Scheduling Planning Execution and Replanning (CASPER)<sup>2</sup> software that replans activities, including downlink, based on science observations in the previous orbit cycles

The onboard science algorithms analyze the images to extract static features and detect changes relative to previous observations. The software uses EO-1 Hyperion instrument images to automatically identify regions of interest including land, ice, snow, water, and thermally hot areas. Repeat imagery using these algorithms can detect regions of change (such as flooding, ice melt, and lava flows). Using these algorithms onboard enables retargeting and search, e.g., retargeting the instrument on a subsequent orbit cycle to identify and capture the full extent of a flood.

Although the ASE software is running on the Earth observing spacecraft EO-1, it will also be used on other interplanetary space missions. On these missions, onboard science analysis will enable capture of short-lived science phenomena. In addition, onboard science analysis will enable data to be captured at the finest time-scales without overwhelming onboard memory or downlink capacities by varying the data collection rate on the fly. The software is currently undergoing infusion on the Mars Exploration Rovers Mission and Mars Odyssey Mission. Examples of future mission applications to use this software include: eruption of volcanoes on Io, formation of jets on comets, and phase transitions in ring systems. Generation of derived science products (e.g., boundary descriptions, catalogs) and change-based triggering will also reduce data volumes to a manageable level for extended duration missions that study long-term phenomena such as atmospheric changes at Jupiter and flexing and cracking of the ice crust on Europa.

The onboard planner (CASPER) generates mission operations plans from goals provided by the onboard science analysis module. The model-based planning algorithms enable rapid response to a wide range of operations scenarios based on a model of spacecraft constraints, including faster recovery from spacecraft anomalies. The onboard planner accepts as inputs the science and engineering goals and ensures high-level goal-oriented behavior.

The robust execution system (SCL) accepts the CASPER-derived plan as an input and expands the plan into low-level commands. SCL monitors the execution of the plan and has the flexibility and knowledge to perform event driven commanding to enable local improvements in execution as well as local responses to anomalies

## II. The EO-1 Mission

Earth Observing-1 (EO-1) is the first satellite in NASA's New Millennium Program Earth Observing series<sup>3</sup>. The goal of the EO-1 primary mission was to develop and test a set of advanced technology land imaging instruments. EO-1 was launched on a Delta 7320 from Vandenberg Air Force Base on November 21, 2000. It was inserted into a 705 km circular, sun-synchronous orbit at a 98.7 degrees inclination. This orbit allows for 16-day repeat tracks, with between 5 (at the equator to 45 degrees) and 16 (at the poles) over-flights per 16-day cycle. For each scene, between 13 to as much as 48 Gbits of data from the Advanced Land Imager (ALI), Hyperion, and Atmospheric Corrector (AC) are collected and stored on the onboard solid-state data recorder.

EO-1 is currently in extended mission, having more than achieved its original technology validation goals. As an example, over 27,000 data collection events have been successfully completed, against original success criteria of 1,000 data collection events. The ASE described in this paper uses the Hyperion hyper-spectral instrument. The

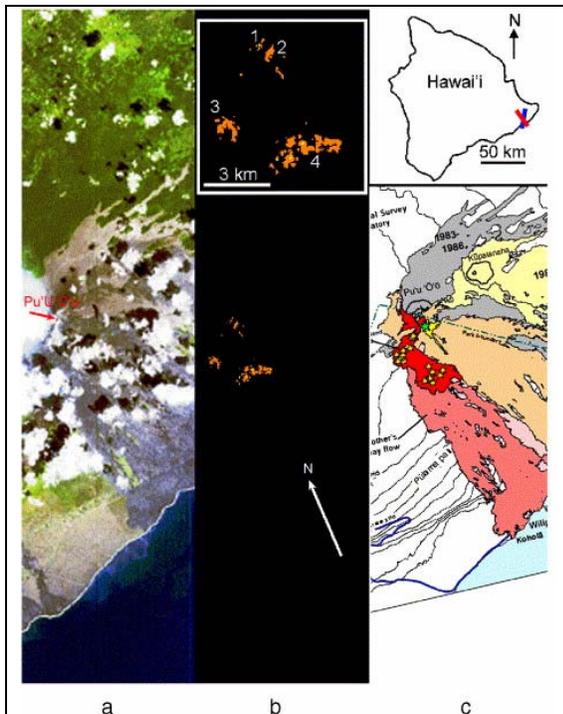
Hyperion is a high-resolution imager capable of resolving 220 spectral bands (from 0.4 to 2.5  $\mu\text{m}$ ) with a 30-meter spatial resolution. The instrument images a 7.7 km by 42 km land area per image and provides detailed spectral mapping across all 220 channels with high radiometric accuracy.

The EO-1 spacecraft has two Mongoose M5 processors. The first M5 is used for the EO-1 command and data handling functions. The other M5 is part of the WARP (Wideband Advanced Recorder Processor), a large mass storage device. Each M5 runs at 12 MHz (for  $\sim 8$  MIPS) and has 256 MB RAM. Both M5's run the VxWorks operating system. The ASE software operates on the WARP M5. This provides an added level of safety for the spacecraft since the ASE software does not run on the main spacecraft processor.

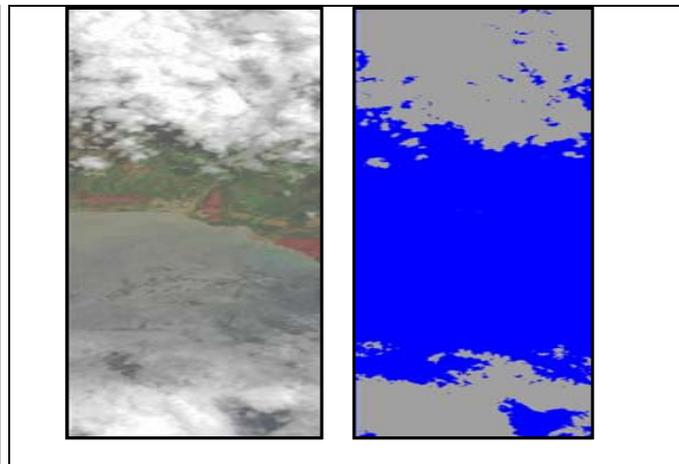
### III. Onboard Science Analysis

The first step in the autonomous science decision cycle is detection of interesting science events. Twelve of the Hyperion spectral bands are used to classify the pixels within each image as land, ice, water, snow, clouds, and fresh lava. Using the pixel classification, a number of science analysis algorithms are being used including:

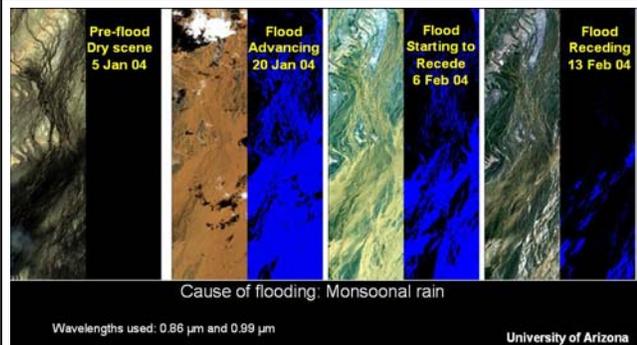
- Thermal anomaly detection – uses infrared spectra peaks to detect lava flows and other volcanic activity. (See Figure 1.)
- Cloud detection<sup>4</sup> – uses intensities at six different spectra and thresholds to identify likely clouds in scenes. (See Figure 2.)
- Flood scene classification – uses ratios at several spectra to identify signatures of water inundation as well as vegetation changes caused by flooding. (See Figure 3.)
- Change detection – uses multiple spectra to identify regions changed from one image to another. This technique is applicable to many science phenomena including lava flows, flooding, freezing and thawing and is used in conjunction with cloud detection. (See Figure 3.)



**Figure 1. Kilauea Volcano. (a) the visible image of Kilauea, Hawaii on 24 January 2004; (b) Thermal Classifier output including an inset enlargement of the active area; (c) shows the USGS – Hawaiian Volcano Observatory map showing volcanically active areas in January 2004. In (c), yellow areas delineate the Martin Luther King (MLK) flows in January 2004.**



**Figure 2. Cloud Detection – visual image at left, grey in right image indicates detected cloud.**



**Figure 3. Flood detection time series imagery of Australia's Diamantina River with visual spectra at left and flood detection map at right.**

Figure 1 contains both the visible image and thermal detection at the Kilauea volcano in Hawaii. The infrared bands are used to detect hot areas that might represent fresh lava flows within the image. In the second third of this image, these hot spots are shown in yellow and orange. The area of hot pixels can be compared with the count of hot pixels from a previous image of the same area to determine if change has occurred. If there has been change, a new image might be triggered to get a more detailed look at the eruption.

Figure 2 shows a Hyperion scene and the results of the cloud detection algorithm<sup>4</sup>. This MIT Lincoln Lab developed algorithm is able to discriminate between cloud pixels and land pixels within an image. Specifically, the grey area in the detection results is clouds while the blue area is land. The results of this algorithm can be used to discard images that are too cloudy. Images with low cloud cover can be further analyzed for science value.

Figure 3 contains 4 EO-1 Hyperion images of the Diamantina River in Australia, along with their corresponding classification images to the right of each image. The first image is a baseline image of the river in a dry state. The black area of the corresponding represents all land pixels with no water. The second image two weeks later shows a large flood area with blue representing water pixels. The final two images show the flood receding over time. The results of the algorithm are compared with land and water counts from a previous image to determine if flooding has occurred. If significant flooding has been detected, the image can be downlinked. In addition, a new goal can be sent to the CASPER planning software to image adjacent regions on subsequent orbits to determine the extent of the flooding.

The JPL developed thermal anomaly algorithms uses the infrared spectral bands to detect sites of active volcanism. There are two different algorithms, one for daytime images and one for nighttime images. The algorithms compare the number of thermally active pixels within the image with the count from a previous image to determine if new volcanism is present. If no new volcanism is present, the image can be discarded onboard. Otherwise, the entire image or the interesting section of the image can be downlinked.

The Arizona State University developed Snow-Water-Ice-Land (SWIL) algorithm is used to detect lake freeze/thaw cycles and seasonal sea ice. The SWIL algorithm uses six spectral bands for analysis.

#### **IV. Onboard Mission Planning**

In order for the spacecraft to respond autonomously to the science event, it must be able to independently perform the mission planning function. This requires software that can model all relevant spacecraft and mission constraints. The Continuous Activity Scheduling Planning Execution and Replanning (CASPER)<sup>2</sup> software performs this function for ASE. CASPER represents the operations constraints in a general modeling language and reasons about these constraints to generate new operations plans that respect spacecraft and mission constraints and resources. CASPER uses a local search approach<sup>5</sup> to develop operations plans.

Because onboard computing resources are scarce, CASPER must be very efficient in generating plans. While a typical desktop or laptop PC may have 2000-3000 MIPS performance, 5-20 MIPS is more typical onboard a spacecraft. In the case of EO-1, the Mongoose V CPU has approximately 8 MIPS. Of the 3 software packages, CASPER is by far the most computationally intensive. For that reason, our optimization efforts were focused on CASPER. In light of the performance constraints, we developed an EO-1 CASPER model that didn't require a lot of planning iterations. For that reason, the model has only a handful of resources to reason about. This ensures that CASPER is able to build a plan in tens of minutes on the relatively slow CPU.

CASPER is responsible for mission planning in response to both science goals derived onboard as well as anomalies. In this role, CASPER must plan and schedule activities to achieve science and engineering goals while respecting resource and other spacecraft operations constraints. For example, when acquiring an initial image, a volcanic event is detected. This event may warrant a high priority request for a subsequent image of the target to study the evolving phenomena. In this case, CASPER modifies the operations plan to include the necessary activities to re-image. This may include determining the next over-flight opportunity, ensuring that the spacecraft is pointed appropriately, that sufficient power, and data storage are available, that appropriate calibration images are acquired, and that the instrument is properly prepared for the data acquisition.

#### **V. Onboard Robust Execution**

ASE uses the Spacecraft Command Language (SCL)<sup>1</sup> to provide robust execution. SCL is a software package that integrates procedural programming with a real-time, forward-chaining, rule-based system. A publish/subscribe software bus, which is part of SCL, allows the distribution of notification and request messages to integrate SCL with other onboard software. This design enables both loose or tight coupling between SCL and other flight software as appropriate.

The SCL “smart” executive supports the command and control function. Users can define scripts in an English-like manner. Compiled on the ground, those scripts can be dynamically loaded onboard and executed at an absolute or relative time. Ground-based absolute time script scheduling is equivalent to the traditional procedural approach to spacecraft operations based on time. In the EO-1 experiment, SCL scripts are planned and scheduled by the CASPER onboard planner. The science analysis algorithms and SCL work in a cooperative manner to generate new goals for CASPER. These goals are sent as messages on the software bus.

Many aspects of autonomy are implemented in SCL. For example, SCL implements many constraint checks that are redundant with those in the EO-1 fault protection software. Before SCL sends each command to the EO-1 command processor, it undergoes a series of constraint checks to ensure that it is a valid command. Any prerequisite states required by the command are checked (such as the communications system being in the correct mode to accept a command). SCL also verifies that there is sufficient power so that the command does not trigger a low bus voltage condition and that there is sufficient energy in the battery. Using SCL to check these constraints and including them in the CASPER model provides an additional level of safety to the autonomy flight software.

## **VI. Technology Validation and Flight Status**

ASE started as a technology experiment. Prior to uploading the software to the EO-1 spacecraft, the software was run through an extensive testing program on several ground-based testbeds. These were low-fidelity testbeds that used software simulators for the spacecraft instruments. As a result, we had to run several tests onboard EO-1 to demonstrate the capabilities of ASE prior to running the technology validation experiments. We slowly built up the autonomy capability by testing each component separately before running an integrated systems test.

The technology was declared fully validated in May 2004 after all 20 onboard autonomy experiments were fully tested. The overall system performed as expected and was considered a success. The validation consisted of the following onboard autonomy experiments run 5 times each:

- Image planning and acquisition
- Downlink
- Data editing
- Image acquisition followed by image retargeting

Since the completion of the technology validation, over 4000 more autonomous data acquisitions have been completed. In addition, we have run over 400 closed-loop executions where ASE autonomously analyzes science data onboard and triggers subsequent observations. The software has been running full-time onboard the EO-1 satellite for the past several months. ASE is now the primary mission planning and control system.

There were 2 important risks to our technology validation approach – one technical and one political. The technical risk was related to spacecraft safety. If the EO-1 satellite was lost due to the ASE software, that would have been a huge setback for onboard spacecraft autonomy. This risk was mitigated using 3 different methods. First, we had an extensive testing program to ensure that the software would operate as expected. Second, we had triple redundancy built into the 3-layered architecture of this autonomy software. Lastly, we ran the software on the solid-state recorder CPU (WARP) rather than the main spacecraft CPU.

The second risk was political. We needed to ensure that the technology validation of our software was convincing enough that scientists would use it on future missions. We had a multi-faceted approach to achieve this goal. First and foremost, we involved (and funded) several scientists in the development of the experiment, software, and operations of the ASE software. The idea is that if the scientists are involved from the start, they will help us develop a useful system and they will promote it to their peers. Another method we employed to ensure future use was to go way beyond the minimal set of validation experiments to show that this software is durable, maintainable, and can achieve increased science. We also started technology infusion early. This effort has so far paid off with infusion underway into the Mars Odyssey and Mars Exploration Rover missions.

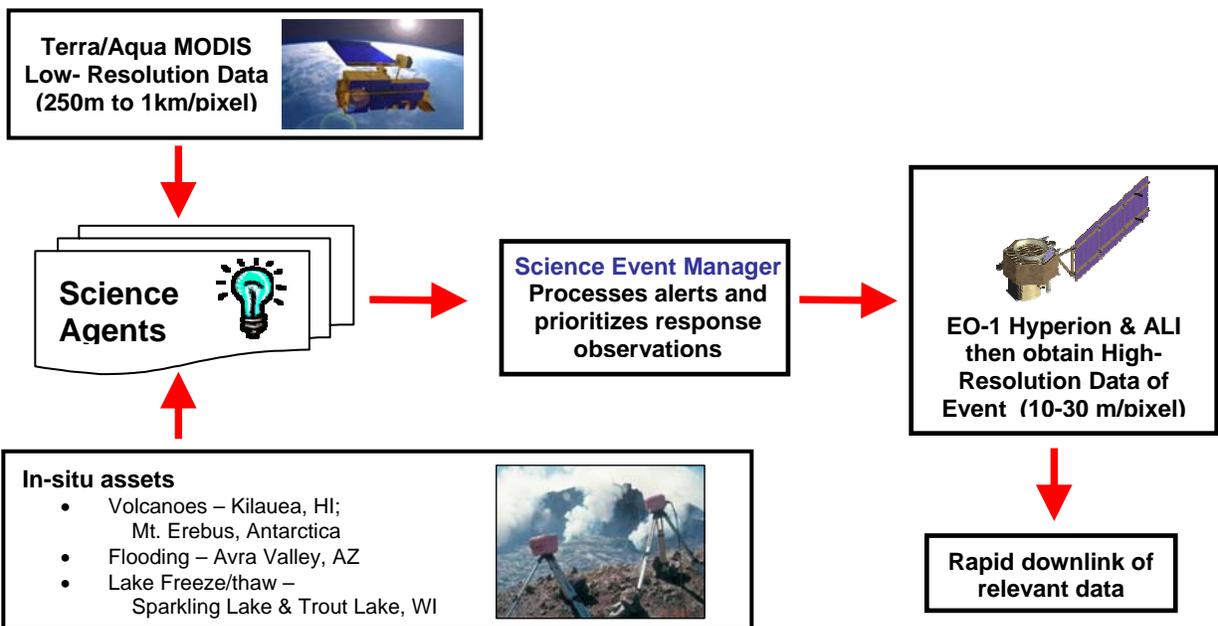
## **VII. The EO-1 Sensorweb**

The use of automated planning onboard EO-1 has enabled a new system-of-systems capability. We have networked the EO-1 satellite with other satellites and ground sensors. This network is linked by software and the Internet to an autonomous satellite observation response capability. (See Figure 4.) This system is designed with a flexible, modular architecture to facilitate expansion in sensors, customization of trigger conditions, and customization of responses.

The EO-1 sensorweb has been used to implement a global surveillance program of science phenomena including: volcanoes, flooding, cryosphere events, and atmospheric phenomena. Using this architecture, we have

performed over 700 sensorweb initiated satellite observations using EO-1. The automated retasking element of the sensorweb consists of several components working together as follows.

1. Science agents for each of the science disciplines automatically acquire and process satellite and ground network data to track science phenomena of interest. These science agents publish their data automatically to the internet each in their own format. In some cases this is via the http or ftp protocol, in some cases via email subscription and alert protocols.
2. Science agents either poll these sites (http or ftp) to pull science data or simply receive emails to receive notifications of ongoing science events. These science agents produce “science event notifications” in a standard XML format which are then logged into a “science event” database.
3. The science event manager processes these science event notifications and matches them up with particular science campaigns as defined by the scientists. When a match occurs, an observation request is generated.
4. These observation requests are processed by the ASPEN automated mission planning system. ASPEN integrates these requests and schedules EO-1 observations according to priorities and mission constraints.
5. For observations that are feasible, an observation request is uplinked to the spacecraft.
6. Onboard EO-1 the ASE software will accommodate the observation request if feasible. In some cases onboard software may have additional knowledge of spacecraft resources or may have triggered additional observations, so some uplinked requests may not be feasible.
7. Later, the science data is downlinked, processed, and delivered to the requesting scientist.



**Figure 4. Sensorweb Detection and Response Architecture**

#### **A. Science Agents**

The science agents encapsulate sensor and science tracking specific information by producing a generic XML alert for each “science event” tracked. The flexibility enabled by these modules allows us to easily integrate with a large number of existing science tracking systems despite the fact that each science tracking system has its own unique data and reporting format. The data formats range from near raw instrument data, to alerts in text format, to periodic updates to a wide range of text formats. The posting methods include http, https, ftp, and email.

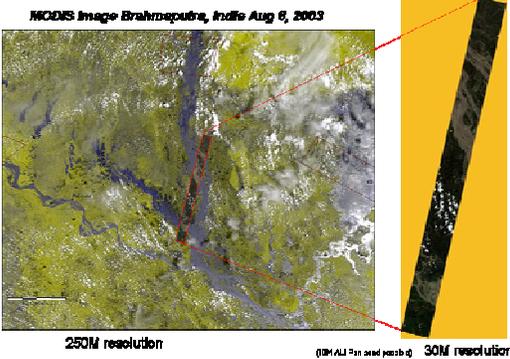
#### **B. Science Event Manager and Science Campaigns**

The Science Event Manager enables scientists to specify mappings from science events to observation requests. It enables them to track frequency and count of events and do logical processing. It also enables them to track based on target names or locations, and other event specific parameters (for example, some tracking systems produce a

confidence measure). As an example, a volcanologist might specify for the Kilauea site that several tracking systems would need to report activity with high confidence before an observation is requested. This is because Kilauea is quite often active. On the other hand, even a single low confidence activity notification might trigger observation of Piton de la Fournaise or other less active sites.

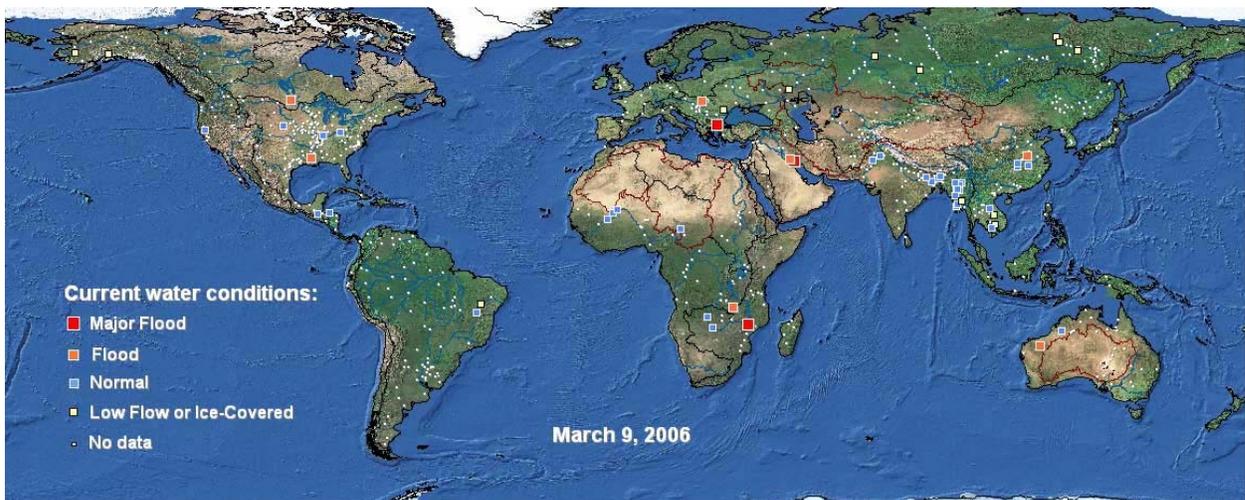
### C. The Wildfire Sensorweb

We have demonstrated the sensorweb concept using the MODIS active fire mapping system. Both the Terra and Aqua spacecraft carry the MODIS instrument, providing morning, afternoon, and two night over-flights of each location on the globe per day (coverage near the poles is even more frequent). The active fire mapping system uses data from the GSFC Distributed Active Archive Center (DAAC), specifically the data with the predicted orbital ephemeris which is approximately 3-6 hours from acquisition. Figure 5 shows the active fire map from October 2003 fires in Southern California.

	
<p><b>Figure 5. Active fire alerts for the October 2003 Southern California Fires. Red indicates active fires. The light blue box illustrates the background region used in the relative threshold detection.</b></p>	<p><b>Figure 6. Examples of low-resolution MODIS imagery (left) and EO-1 imagery (right) from the Flood Sensorweb capturing Brahmaputra River flooding in India, August 2003.</b></p>

### D. The Flood Sensorweb

The flood sensorweb uses the Dartmouth Flood Observatory (DFO) Global Active Flood Archive to identify floods in remote locations automatically based on satellite data. The DFO flood archive publishes web-based flood alerts based on MODIS, QuikSCAT, and AMSR-E<sup>6</sup> satellite data. The flood sensorweb utilizes the DFO QuikSCAT atlas because it is not affected by cloud cover over flooded areas.



**Figure 7. Dartmouth Flood Observatory Global Flood Alerts for March 2006.**

In the flood sensorweb, active flooding alerts prime locations of known scientific interest trigger EO-1 observations at gauging reaches. Gauging reaches are river locations whose topography is well understood. Flood discharge measurements at gauging reaches can be used to measure the amount of water passing through a flooded region and can be compared with remotely sensed data. The end effect of the flood sensorweb is to increase the amount of high resolution remote sensing data available on flooding events in prime locations of interest (e.g., gauging reaches) and times of interest (e.g. when active flooding occurs). Imagery from an August 2003 flood sensorweb demonstration capturing flooding in the Brahmaputra River, India, is shown in Figure 6. An example of the DFO Flood Map is shown in Figure 7.

#### **E. The Volcano Sensorweb**

In the volcano sensorweb, MODIS, GOES7, and AVHRR sensor platforms are utilized to detect volcanic activity. These alerts are then used to trigger EO-1 observations. The EO-1 Hyperion instrument is ideal for study of volcanic processes because of its great sensitivity range in the infra-red spectrum.

The GOES7 and AVHRR alert systems provide excellent temporal resolution and rapid triggering based on thermal alerts. The GOES-based system looks for locations that are: hot, is high contrast from the surrounding area, and not visibly bright. Additionally, hits are screened for motion (to eliminate cloud reflections) and persistence (to remove instrument noise). The GOES alert can provide a web or email alert within 1 hour of data acquisition.

We have also linked into in-situ sensors to monitor volcanoes. The Hawaiian Volcano Observatory (HVO) has deployed numerous instruments on the Kilauea region in Hawaii. These instruments include tiltmeters, gas sensors, and seismic instrumentation. These sensors can provide indications that collectively point to a high-probability, near-term eruption thereby triggering a request for high-resolution, EO-1 imagery. The University of Hawaii has also deployed infra-red cameras<sup>8</sup> to a number of volcanic sites worldwide (e.g., Kilauea, Hawaii; Erte Ale, Ethiopia; Soufriere Hills, Montserrat; Colima and Popocatepetl, Mexico). These infra-red cameras can provide a ground-based detection of lava flows based on thermal signatures, thereby alerting the sensorweb.

#### **F. Cryosphere Sensorweb**

Many freeze/thaw applications are also of interest. This includes the phenomena of glacial ice breakup, sea ice breakup, melting, and freezing, lake ice freezing and thawing, and snowfall and snowmelt. Using QuikSCAT data we are tracking snow and ice formation and melting and automatically triggering higher resolution imaging such as with EO-1.

In collaboration with the Center for Limnology of the University of Wisconsin at Madison, we have linked into data streams from the Trout Lake station to use temperature data to trigger imaging of the sites to capture transient freezing and thawing processes.

### **VIII. Past Operations Flow**

The EO-1 spacecraft<sup>3</sup> is operated out of the EO-1 Mission Operations Control Center (MOCC) at the Goddard Space Flight Center (GSFC). The Mission Operations Planning and Scheduling System (MOPSS) was used for long-term planning. The Advanced Spacecraft Integration and System Test (ASIST) tool is used for real-time operations including sending commands and receiving and displaying telemetry. Much of the EO-1 ground and flight systems are similar to the Microwave Anisotropy Probe (MAP)<sup>9</sup> systems. Figure 8 contains the past EO-1 planning and operations flow.

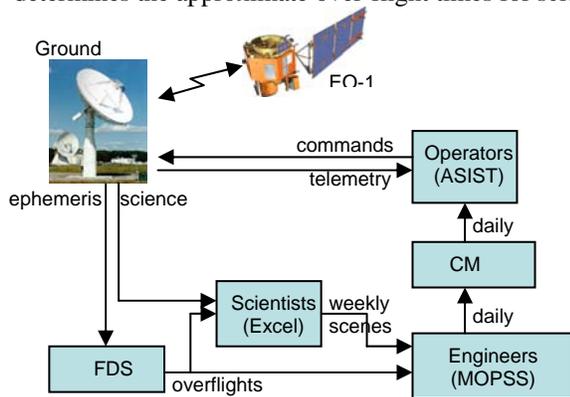
A good approximation of the spacecraft orbit can be predicted about a week in advance. Therefore, the spacecraft schedule of activities was generated on a weekly basis. But because a 1-day orbit prediction is more accurate, the detailed commands were generated and uploaded on a daily basis.

#### **G. Past Weekly Operations**

In the past, the U. S. Geological Survey (USGS) managed the science requests for EO-1. These included standing and one-time requests from the EO-1 science team, the USGS, and from paying external customers. The first step in operations is to process the long term plan (LTP) of requests received by the USGS. This plan is a list of targets that would be visible for the upcoming week, including the orbits in which they will be visible.

The ground contact support for EO-1 is managed out of the White Sands Complex (WSC). There are several stations in a ground network (GN) available to EO-1, including the primary sites in Poker Flats, Alaska and Svalbard, Norway. The next step in operations is to process the GN schedule received by the WSC. This is list of scheduled contacts between EO-1 and the ground stations. Next, the Flight Dynamics Support System (FDSS) at

GSFC is used to calculate the spacecraft ephemeris, predicting the spacecraft orbit through the upcoming week. This determines the approximate over-flight times for science targets and ground station contacts.



**Figure 8. Pre-Autonomy EO-1 Operations Flow**

done, an X-band contact must be scheduled to downlink the science data to Earth. These activities are selected at the same weekly science meeting when images are selected. About one X-band contact every other orbit is selected to keep the WARP from overflowing.

## H. Past Daily Operations

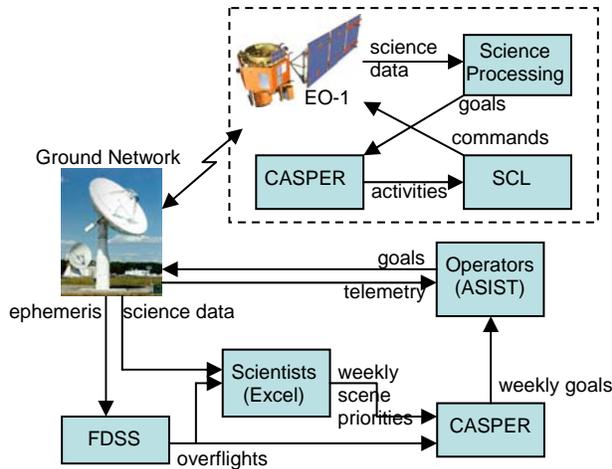
After the weekly science meeting, the mission planner would use MOPSS to begin scheduling the 1-week set of activities. First, spacecraft maneuver commands are scheduled for each scene. Using the ephemeris, parameter values are calculated for the maneuver commands that will point the instruments toward the target. After each scene is imaged, another maneuver command is added to the schedule to point the spacecraft at nadir. Next, because the maneuvers use reaction wheels, more commands must be added to bias and de-saturate the wheels. When the wheels change directions, they are less stable and may produce jitter during the observation. Therefore, prior to a group of scenes, the wheels are biased to a non-zero spin rate at the times when data will be collected for the scenes. After a group of scenes, the wheels are desaturated by biasing them to a zero spin rate. This provides the maximum flexibility for spinning the wheels in either direction for subsequent biasing.

While the original manual selection of scenes and contacts are done with the spacecraft requirements in mind, scheduling the details for these activities may still reveal conflicts. MOPSS identifies these conflicts and the mission planner would need to resolve them manually. When all conflicts are resolved for the next day, the activities are sent from MOPSS to the Command Management System (CMS) where the sequence is generated and prepared for uplink to the spacecraft. The commands for a given day are typically prepared the day before, then uplinked using ASIST on the next available ground contact. This is performed at the latest reasonable time so that the most accurate ephemeris data can be used to generate the command parameters, and because the sequence is difficult to change once it has been loaded onboard.

Re-planning for new science requests, while possible, is difficult in this scenario. After executing an original set of requests, the scientists must wait for the image products to be delivered. This includes waiting for the next X-band downlink, and often includes several days of waiting for the data (stored on tape) to be manually shipped from the ground stations. Once the data arrives, the scientists can run any number of manual or automated analyses on the images. The results of the analyses may suggest a change in priorities for the upcoming requests. For example, detecting a fleeting event such as a forest fire may increase the priority of a repeat scene of the same target. This request is then made at the next weekly meeting. However, if the meeting has already occurred, then the change may require manual rescheduling steps, and must be negotiated with the operations team. If the command sequence has already been uploaded, then the change is difficult and typically not worth the risk.

## IX. Current Operations Flow

The Autonomous Sciencecraft Experiment (ASE) team developed advanced operations software for the EO-1 mission. Much of this software is used both on ground workstations for mission operations and on the flight processor for autonomous operations. For example, we make use of the Automated Scheduling Planning Environment (ASPEN)<sup>5</sup>, the ground version of the onboard CASPER planner. In this section, we discuss the impact



of this software on the weekly and daily operations of EO-1. Figure 9 contains a flow diagram of the current EO-1 operations process including the ASE software. Table 1 contains a comparison of the previous operations steps with the modified steps that include ASE.

**Figure 9. EO-1 Operations Flow with ASE**

Step	Current Ops	Modified Ops
1	Process long term plan (LTP) requests	Process long term plan (LTP)
2	Process JPL requests and convert to EO-1 LTP	Process JPL requests
3	Process ground network (GN) schedule	Process ground network (GN) schedule
4	Process ephemeris and overflights	Process ephemeris and overflights
5	Manually prioritize science targets	Manually prioritize science targets
6	Manually select science targets	ASPEN selects science targets
7	Manually schedule downlinks	ASPEN schedules downlinks
8	Manually schedule maneuvers	ASPEN schedules maneuvers
9	Manually schedule momentum wheel commands	ASPEN schedules momentum wheel commands
10	Generate sequence and uplink	Uplink goals
11	Load time-tagged sequence into onboard queue	CASPER loads goals and generates plan
12	Execute sequence	SCL executes and monitors sequence
13	Manually reprioritize science targets	Science algorithms reprioritize science targets
14	Manually select replacement targets	Science algorithms select replacement targets
15	Manually reschedule	CASPER reschedules
16	Generate sequence and uplink	No uplink required

**Table 1. Comparison of Operations Process Steps Before and After ASE**

### I. Weekly Operations

For the weekly science planning, ASPEN is used to lighten the workload of the scientists and engineers. Rather than *selecting* science targets, which requires knowledge of the spacecraft operations constraints, the scientists need only to *prioritize* the LTP for the upcoming week. ASPEN is then used to select the highest priority scenes while respecting spacecraft and operations constraints.

ASPEN is also used to schedule downlinks for the observations. The GN schedule identifies the set of X-band downlink opportunities and ASPEN uses its model of the WARP to predict when the memory will reach capacity. Using this model, it automatically adds X-band downlinks and file delete activities to free up space on the recorder. As with all activities, these are scheduled where allowed by the over-flights and spacecraft constraints.

Finally, ASPEN interfaces with the Flight Dynamics Support System (FDSS) and generates the required maneuver and wheel bias commands. The FDSS software uses the spacecraft ephemeris to provide the required parameters for the commands. The ephemeris file is generated using estimates of the spacecraft position and velocity vectors. Using GPS data, these vectors are calculated onboard for the ACS, but the velocity vectors are not accurate enough to make long-term predictions. Therefore, weekly predictions are made on the ground using tracking data from the GN.

### J. Daily Operations

With the planner operating onboard the spacecraft, we do not need to uplink the detailed command sequence, but only the high-level requests for scenes, downlinks, maneuvers, and wheel biasing. When CASPER receives these

goals, it will expand them into more detailed activities and schedule all activities at non-conflicting start times. Pending activities are continuously sent to SCL where the appropriate commands are executed and monitored.

This also means that we can uplink the entire week of goals rather than one day at a time. But, as the estimates for orbital parameters change, we need to send commands to the planner to change the relevant parts of the plan. This includes changes to scene start times and to parameters for maneuvers and wheel bias activities. When the planner receives these commands, it makes these and other changes necessary to maintain consistency in the plan. Using the ephemeris and the Flight Dynamics Support System (FDSS) on the ground, these commands must be uplinked, presumably on a daily basis. However, the onboard ephemeris is accurate enough for 1-day predictions and could be used to generate these daily plan updates. This would require additional work to port the FDSS (currently implemented in Matlab) to the flight processor and operating system. Another alternative would be to skip the daily updates and use the less accurate (generated weekly) parameters for pointing, biasing, and image timing. This would result in slightly degraded science data, but possibly still within acceptable limits. Ultimately, this work would close the loop and allow us to fly autonomously for a full week. The final decision on the actual implementation will depend on available project resources.

Re-planning scenarios become much easier with the addition of the ASE flight software. First, the science products are immediately available onboard after executing a scene request. The onboard science algorithms can start analyzing the data much earlier than if the analysis were done on the ground. The results of the analysis can then trigger new requests which are immediately sent to CASPER onboard. After receiving the new requests, CASPER will change the plan to accommodate the requests while maintaining consistency with spacecraft constraints. Onboard analysis and re-planning takes only minutes compared to ground-based operations which may take days.

To re-plan science activities onboard, we also need to re-plan the associated maneuver and wheel bias activities which were originally planned on the ground. The parameters for these activities, calculated by the FDSS, depend on the prior spacecraft orientation and wheel speed. However, by making a few simple assumptions, these activities can be scheduled onboard without requiring parameter recalculations. Specifically, if we assume that we always slew to nadir after a scene, then all maneuvers will begin at nadir and the parameters will remain constant regardless of the order of the scenes. If we also assume that the wheels are biased prior to each scene and desaturated after each scene, again, the parameters remain constant. Therefore, CASPER can change the plan in flight using values pre-calculated by the FDSS. The disadvantage is that the plan will contain unnecessary activities and may not be optimal. However, we do not expect this impact to be significant.

## **X. New Ground Software**

Additional ground support software has been put in place to integrate the ASE architecture into EO-1 operations procedures. This software package interfaces with the science and operations teams to coordinate the selection of observations, pre-flight testing, and post-flight data management. A web-based interface manages each of the following steps:

1. Generating a list of potential observations for the upcoming week.
2. Providing an interface for the ASE science team to select observations and science analysis parameters.
3. Converting the selected observations to CASPER science goals.
4. Validating the autonomous execution of these observations on the ground testbeds.
5. Sending the validated goals to the EO-1 operations team for uplink to ASE on EO-1.
6. Testing
7. Processing and validating the telemetry and science data returned from the autonomous execution of the science goals onboard EO-1.
8. Logging and cataloging the products from each operations step.
9. Sending email notifications to the relevant personnel for each step.

Additionally, a web-based interface was constructed to enable EO-1 operations personnel to request engineering activities for the generated schedules. These include instrument calibrations, instrument outgassing activities, and maneuvers. With the exception of maneuvers, each of these activities is scheduled and expanded out to appropriate commands by the automation software. For maneuvers, ASPEN blocks out an appropriate time window and the flight dynamics team generates the exact command sequence required for orbit maintenance and it is inserted into the schedule.

## **XI. Technology Infusion**

The science component of the ASE software will soon be used onboard the Mars Exploration Rovers (MER) Mission to enable onboard detection and summarization of atmospheric events (dust devils and clouds). Recent explorations on the Martian surface have revealed an environment far more dynamic than previously believed. In particular, the atmosphere of Mars is very dynamic. Dust devils and clouds are dynamic atmospheric features that have been observed by the MER. These high science value events have been the subject of considerable study. Both dust devil and cloud detection campaigns have been conducted, but in general these are rare events. For example, only around 10-25% of the cloud campaign images collected have clouds in them. Prior campaigns have involved collecting images at fixed times for return to Earth. This is an inefficient use of downlink bandwidth as the majority of images do not contain dust devils or clouds.

To improve the effectiveness of atmospheric imaging campaigns, we have developed a different approach. In this approach onboard processing is used to screen images for the science features of interest (i.e., clouds and dust devils). Using this approach, many images can be collected onboard resulting in a much greater time range for capturing the rare phenomena. Even when the images cannot be down-linked (such as when too many events are detected), compact summary statistics on the number and type of events can still be down-linked to provide valuable information. The code has been integrated with the MER flight software, and is scheduled for upload to the MER rovers in May 2006.

The science component of the ASE software is also under development for the Mars Odyssey Mission to enhance science return from the THEMIS instrument with planned operational capability in the 2nd extended mission (beginning in Fall 2006). In this application, the ASE software will:

- Track the seasonal variation in the CO<sub>2</sub> ice caps
- Detect thermal anomalies
- Track dust storms
- Track Martian clouds

The MER THEMIS instrument is powered on almost 100% of the time although only 5% of the data is collected due to bandwidth limitations. Using the ASE science algorithms, the THEMIS images can be analyzed onboard for the existence of thermal anomalies, dust storms, and clouds. Only the images that contain these events will be returned to Earth. This will allow the Odyssey Science Team to make use of the other 95% of the data that is currently lost. Detecting thermal anomalies would be a very low probability event but of very high science value. Also, the boundaries of the CO<sub>2</sub> ice caps can be detected and only the image of the boundary will be returned.

In addition, we are researching autonomous science and sensorweb applications for magnetosphere events for space weather, change detection on Io and Europa, and storm tracking on Jupiter.

## **XII. Lessons Learned**

We learned some important lessons related to the processing capability for using autonomous science onboard. The EO-1 spacecraft contains two very limited capability Mongoose V computers. There were two issues related to these computers. First, it was very advantageous from a safety standpoint that the autonomy software was not running on the main flight control computer. Any problems resulting from the failure of the ASE software will generally result in lost data collects – a much more tolerable failure that bringing down the flight control computer. The second issue was the limited performance (8 MIPS) of the EO-1 CPU's. The low performance necessitated creating simplified planning models so that the planning could be performed in a reasonable time. In addition, we were not able to use previously developed computationally intensive generalized science algorithms.

The performance issue also extends to the infusion targets. The Mars Odyssey and MER CPU's do not have enough performance and memory to run the planning component of ASE. Other future missions will have data intensive instruments such as radar. In these cases, it may make sense to use a dedicated CPU/FPGA combination to process the data and run the autonomous science software. This new architecture will also allow image registration for change detection as well as more complicated machine learning science algorithms.

## **XIII. EO-1 Operational Cost Savings as a Result of Autonomous Science**

The ASE software has been flying onboard EO-1 from 2003 to 2006. Both flight and ground elements of the software have enabled large portions of the observation planning, sequence generation, and command load uplink processes to be automated for EO-1, resulting in considerable cost savings while maintaining or improving mission science return. In order to compute the cost savings from ASE automation the following steps were performed:

1. Operations costs for operating the EO-1 mission for basic science capability but without the ASE software was estimated. This basic science capability included: averaging approximately 100 observations per week, ability to routinely retask to priority targets with 24 hours (or less) notice, retention of the basic spacecraft observation capability (e.g., minimal risk to the spacecraft, reasonable use of consumables).
2. Operations costs for operating the EO-1 mission with the same capability but utilizing the ASE software to automate to reduce operations costs wherever possible.

The cost savings are the difference between 1 and 2 above. In estimating both 1 and 2 above, the EO-1 Flight Operations Team (FOT) developed estimates by a bottom up calculation by the doing functions (e.g. flight dynamics, operators, sequence generation). Whenever possible the computation of 1 was derived from actual operations expenditures in the prior operations of EO-1. The computation of 2 was based on the experience of operating ASE through September 2005.

	<b>EO-1 before ASE (\$K)</b>	<b>EO-1 using ASE (\$K)</b>	<b>Savings (\$K)</b>
Mission planning & sequence generation (reduction in personnel)	800	200	600
Observation Planning	1140	720	420
<b>Total</b>	<b>1940</b>	<b>920</b>	<b>\$1020K</b>

**Figure 10. Annual Cost & Savings for EO-1 Operations**

Mission planning and sequence generation savings are due to automation of portions of the baseline schedule generation, ground tracking station allocation, sequence generation, command load generation, and uplinking of goal files which replace command loads. Observation planning savings are due to automating portions of the observation selection process. Other indirect savings have been enabled. Because goal file uploads occur automatically, command files are no longer needed to be uploaded on weekends – enabling reduction of weekend operator staffing (2 days per week). These cost savings have been validated with the continuing operations of EO-1 during FY 2006 (e.g. from 1 October 2005 – 1 February 2006). Operations of the EO-1 satellite during this period have been performed within the described budget and science return has met or exceeded the guideline requirements.

#### **XIV. Related Work & Summary**

In 1999, the Remote Agent experiment (RAX)<sup>10</sup> executed for a few days onboard the NASA Deep Space One mission. RAX is an example of a classic three-tiered architecture<sup>11</sup>, as is ASE. RAX demonstrated a batch onboard planning capability (as opposed to CASPER’s continuous planning) and RAX did not demonstrate onboard science.

ASE on EO-1 demonstrates an integrated autonomous mission using onboard science analysis, replanning, and robust execution. The ASE performs intelligent science data selection that leads to a reduction in data downlink. In addition, the ASE increases science return through autonomous retargeting. Demonstration of these capabilities onboard EO-1 will enable radically different missions with significant onboard decision-making leading to novel science opportunities. The paradigm shift toward highly autonomous spacecraft will enable future NASA missions to achieve significantly greater science returns with reduced risk and reduced operations cost. We have also described ongoing work to link together automated science event tracking system with an autonomous response capability based on automated planning technology. Demonstration of these sensorweb capabilities will enable fast responding science campaigns and increase the science return of spaceborne assets. .

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