

**Invited Talk:**  
**The EO-1 Autonomous Sciencecraft**  
**and Prospects for Future Autonomous Space Exploration**

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***Abstract.** An Autonomous Science Agent is currently flying onboard the Earth Observing One Spacecraft. With this software the spacecraft autonomously detects and responds to science events occurring on the Earth including volcanoes, flooding, and cryosphere. The package includes software systems that perform science data analysis, deliberative planning, and run-time robust execution. This autonomy software has enabled a 100x increase in science return and has been the primary operations system for the Earth Observing One Mission since November 2004. In this talk I describe the revolutionary new science enabled by onboard autonomy as well as impact on extended missions such as the Mars Exploration Rovers and Mars Odyssey as well as future missions in development.*

## **1 Introduction**

The Autonomous Sciencecraft Experiment (ASE) is currently flying autonomous agent software on the Earth Observing One (EO-1) spacecraft [Chien et al. 2005a]. This software uses several integrated autonomy technologies to enable autonomous science. Multiple algorithms to detect the occurrence of science events based on remote sensing imagery analyze science data onboard. These algorithms are used to downlink science data only on change, and detect features of scientific interest such as volcanic eruptions, flooding, ice breakup, and presence of cloud cover. These onboard science algorithms are inputs to onboard decision-making algorithms that then modifies the spacecraft observation plan to capture high value science events. This new observation plan is then be 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 Autonomous Sciencecraft Experiment (ASE) effort to develop and deploy the Autonomous

Science Agent on the Earth Observing One spacecraft.

The ASE onboard flight software includes several autonomy software components:

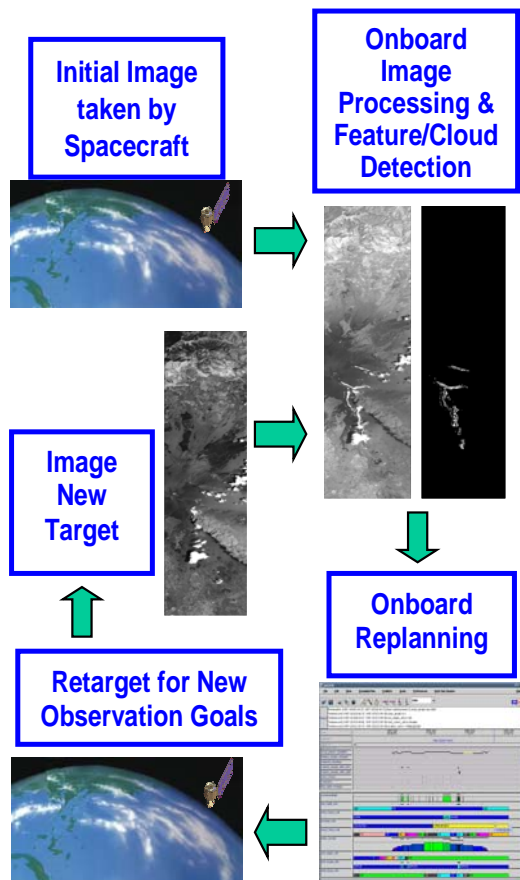
- Onboard science algorithms [Burl et al. 1998, Davies et al. 2001, Davies et al. 2005] that analyze the image data to detect trigger conditions such as science events, “interesting” features, changes relative to previous observations, and cloud detection for onboard image masking
- Robust execution management software using the Spacecraft Command Language (SCL) [Interface & Control] package to enable event-driven processing and low-level autonomy
- The Continuous Activity Scheduling Planning Execution and Replanning (CASPER) [Chien et al. 2000] software that replans activities, including downlink, based on science observations in the previous orbit cycles

A typical ASE scenario involves monitoring of active volcano regions such as Mt. Etna in Sicily, Italy. ASE has already been used to perform similar demonstrations. The ASE concept is described as follows:

1. Initially, ASE has a list of science targets to monitor that have been sent as high-level goals from the ground.
2. As part of normal operations, CASPER generates a plan to monitor the targets on this list by periodically imaging them with the Hyperion instrument. For volcanic studies, the infra-red and near infra-red bands are used.
3. During execution of this plan, the EO-1 spacecraft images Mt. Etna with the Hyperion instrument.
4. The onboard science algorithms analyze the image and detect a fresh lava flow, or active vent. If new activity is detected, a science goal is generated to continue

monitoring the volcanic site. If no activity is observed, the image is not downlinked.

5. Assuming a new goal is generated, CASPER plans to acquire a further image of the ongoing volcanic activity.
6. The SCL software executes the CASPER generated plan to re-image the site.
7. This cycle is then repeated on subsequent observations.



**Figure 1.** Autonomous Science Scenario

Building autonomy software for space missions has a number of challenges.

1. Limited, intermittent communications to the agent. A typical spacecraft in low earth orbit (such as EO-1) has 5 x 10-minute communications opportunities per day. This means that the spacecraft must be able to operate for long periods of time without supervision. For deep space missions the spacecraft may be in communications far less frequently. Some deep space missions only contact

the spacecraft once per week, or even once every several weeks.

2. Spacecraft are very complex. A typical spacecraft has thousands of components, each of which must be carefully engineered to survive rigors of space (extreme temperature, radiation, physical stresses). Add to this the fact that many components are one-of-a-kind and thus have behaviors that are hard to characterize.
3. Limited observability. Because processing telemetry is expensive, onboard storage is limited, and downlink bandwidth is limited, engineering telemetry is limited. Thus onboard software must be able to make decisions on limited information and ground operations teams must be able to operate the spacecraft with even more limited information.
4. Limited computing power. Because of limited power onboard, spacecraft computing resources are usually very constrained. An average spacecraft CPUs offer 25 MIPS and 128 MB RAM – far less than a typical personal computer. Our CPU allocation for ASE on EO-1 is 4 MIPS and 128MB RAM.
5. High stakes. A typical space mission costs hundreds of millions of dollars, any failure has significant economic impact. The total EO-1 Mission cost is over \$100 million dollars. Over financial cost, many launch and/or mission opportunities are limited by planetary geometries. In these cases, if a space mission is lost it may be years before another similar mission can be launched. Additionally, a space mission can take years to plan, construct the spacecraft, and reach their targets. This delay can be catastrophic.

Of the above aspects of spacecraft autonomy, two critical issues are:

1. Extreme reliability – because of the extreme cost of space missions and inability to access the spacecraft except by communications the software agent must be exceptionally reliable.
2. CPU and RAM performance: spacecraft have extremely limited CPU and RAM (in our case 4 MIPS and 128MB RAM) yet must adhere to at least soft, real-time constraints.

In the remainder of this paper we describe the ASE software architecture and components. We then discuss how the issues of reliability and performance affected the software architecture. For a more in-depth discussion of the validation and testing process used for ASE see [17].

## 2 The EO-1 Mission

Earth Observing-1 (EO-1) is the first satellite in NASA's New Millennium Program Earth Observing series [Goddard Space Flight Center]. The primary focus of EO-1 is 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 3 over flights per 16-day cycle with a less than 10-degree change in viewing angle. For each scene, over 20-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 at high rates.

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 7.5 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 ~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.

## 3 Autonomy Software Architecture

The autonomy software on EO-1 is organized into a three-layer architecture [Gat et al. 1998] (See Figure 2.). At the highest level of abstraction, the Continuous Activity Scheduling Planning Execution and Replanning (CASPER) software is responsible for mission planning functions.

CASPER schedules science activities while respecting spacecraft operations and resource constraints. The duration of the planning process is on the order of tens of minutes. CASPER scheduled activities are inputs to the Spacecraft Command Language (SCL) system, which generates the detailed sequence commands corresponding to CASPER scheduled activities. SCL operates on the several second timescale. Below SCL the EO-1 flight software is responsible for lower level control of the spacecraft and also operates a full layer of independent fault protection. The interface from SCL to the EO-1 flight software is at the same level as ground generated command sequences. The science analysis software is scheduled by CASPER and executed by SCL in batch mode. The results from the science analysis software result in new observation requests presented to the CASPER system for integration in the mission plan.

This layered architecture was chosen for two principal reasons:

1. The layered architecture enables separation of responses based on timescale and most appropriate representation. The flight software level must implement control loops and fault protection and respond very rapidly and is thus directly coded in C. SCL must respond (in seconds) quickly and perform many procedural actions. Hence SCL uses as its core representation scripts, rules, and database records. CASPER must reason about longer term operations, state, and resource constraints. Because of its time latency, it can afford to use a mostly declarative artificial intelligence planner/scheduler representation.
2. The layered architecture enables redundant implementation of critical functions – most notable spacecraft safety constraint checking. In the design of our spacecraft agent model, we implemented spacecraft safety constraints in all levels where feasible.

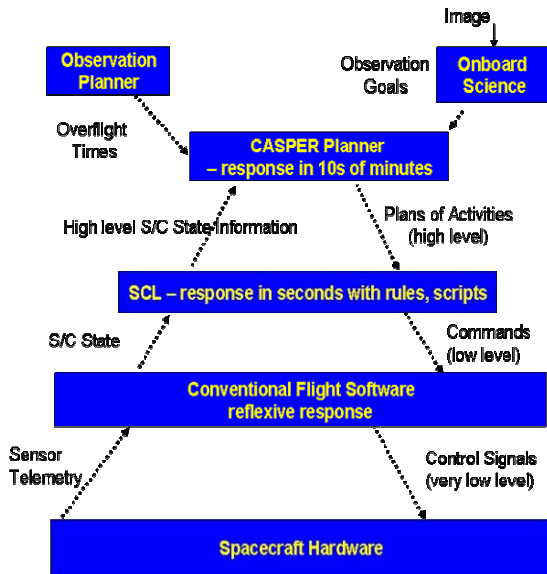


Figure 2. Autonomy Software Architecture

For further details on the Autonomous Spacecraft Software please see [Chien et al. 2005a].

## Flight Status

The ASE software has flown beginning in the Fall of 2003 in a steady progression to full operations. Beginning in November 2004, ASE became the primary operations system for the Earth Observing One Mission. As this paper goes to press (July 2005) ASE has acquired over 2400 images autonomously. ASE has documented a 100x increase in science return as measured by (# of events captured / MB downlinked). ASE has also enabled a \$1.5M/yr reduction in operations costs for the Earth Observing One mission.

A more recent effort includes teaming with the NASA Ames Research Center to fly the Livingstone 2 Mode Identification and Diagnosis software [Hayden et al. 2004]. This software has been flying in a monitoring mode since Fall 2004. The Livingstone 2 experiment demonstrates tracking of multiple fault hypotheses, a capability not demonstrated in the Remote Agent Experiment in 1999.

## 10 Contribution to Current and Future Space Missions,

The ASE enables demonstration of onboard science in an Earth-directed mission, but has direct relevance to a large number of deep space missions throughout the solar system.

Specifically, the ASE onboard science processing has numerous applications to Space Science Missions. For example, in Europa orbiter and lander missions, onboard science processing could be used to autonomously:

Already, elements of autonomous science are being infused into extended missions. A capability for onboard science for the Mars Exploration Rovers is well under development. This software enables onboard software to detect and track transient features such as dust devils and clouds. This software is planned for upload in January 2006. With this onboard science software, the MER rovers will be able to acquire larger amounts of imagery searching for transient atmospheric features (e.g. dust devils and clouds). The software will then analyze the imagery onboard to determine which images are most likely to contain the science features of interest. After sufficient flight validation, only images determined by the onboard software will be downlinked, thereby increasing the number of phenomena images. In some cases, where the number of detections is too large for onboard memory allocations, the onboard software will extract key features of the events (such as size, morphology, and time of occurrence for the dust devils) and only this information will be downlinked. By increasing the density of events in imagery mission science return can be improved.

Another infusion in progress is a collaboration with the THEMIS instrument team for the Mars Odyssey Mission. In this effort, the THEMIS instrument software will be upgraded with a capability to: track onboard: variations in the Co2 frost cap [Wagstaff et al. 2005], search for thermal anomalies; track dust storms, and track clouds. This effort is well underway with a proposed infusion during the Mars Odyssey 2<sup>nd</sup> extended mission (beginning in Fall 2006).

This mature mission capability will lead to vastly improved science on a wide range of missions [Davies et al. 2001, Chien et al. 2003, Davies et al. 2005]. Other mission concepts enabled or enhanced by autonomy technology we list below:

Earth observing missions – could respond to dynamic science alerts utilizing networks of orbital and in-situ sensors. Preliminary efforts in this vein to monitor volcanoes, floods, and cryosphere events are described in [Chien et al. 2005b]. Earth observing missions could also perform data quality control to reject cloudy data, or product high level science alerts (an early form of this are the volcano alerts provided by the EO-

1 volcano sensorweb, operational for over a year now).

Planetary missions – could track a wide range of transient phenomena. Missions to the Jovian system could track atmospheric events, lightning, magnetospheric events, Io volcanism, and European crustal changes. Also rovers could use autonomous science to perform closed loop geological or other investigations [Davies et al. 1999, Castano et al. 2005, Estlin et al. 2005]. Multiple rovers could also use multi-agent autonomy [Estlin et al. 2005, Barrett 2005].

Sun-Earth connection missions – could track coronal mass ejections, sun pointed instruments (e.g. STEREO A and B, SOHO) could monitor for events that could automatically trigger Earth orbiting magnetospheric instruments (e.g. IMAGE, MMC) to change their data gathering modes. These missions could also use multi-agent autonomy [Clement & Barrett 2003].

Small-body missions – could detect and respond to short-lived science events such as outgassing/jets. Event driven response could enable a spacecraft to image such high interest events and protect instruments if necessary.

Astrophysics – could respond to detected science events such as supernovae, gamma ray bursts (e.g. SWIFT) and image or notify other assets.

### Related Work, and Summary

In 1999, the Remote Agent experiment (RAX) [Muscettola et al. 1998] executed for a few days onboard the NASA Deep Space One mission. RAX is an example of a three-tiered architecture, as is ASE. RAX demonstrated a batch onboard planning capability (as opposed to CASPER's continuous planning) and RAX did not demonstrate onboard science. PROBA [ESA] is a European Space Agency (ESA) mission demonstrates onboard autonomy and launched in 2001. However, ASE has more of a focus on model-based autonomy than PROBA.

The Three Corner Sat (3CS) University Nanosat mission will be using the CASPER onboard planning software integrated with the SCL ground and flight execution software [Chien et al. 2001a]. The 3CS mission launched in December 2004 but suffered a launch vehicle deployment failure. The 3CS autonomy software includes onboard science data validation, replanning, robust execution, and multiple model-based anomaly detection. The 3CS mission is considerably less complex than EO-1 but still represents an

important step in the integration and flight of onboard autonomy software.

More recent work from NASA Ames Research Center is focused on building the IDEA planning and execution architecture [Muscettola et al. 2002]. In IDEA, the planner and execution software are combined into a “reactive planner” and operate using the same domain model. A single planning and execution model can simplify validation, which is a difficult problem for autonomous systems. For EO-1, the CASPER planner and SCL executive use separate models. While this has the advantage of the flexibility of both procedural and declarative representations, a single model would be easier to validate. We have designed the CASPER modeling language to be used by domain experts, thus not requiring planning experts. Our use of SCL is similar to the “plan runner” in IDEA but SCL encodes more intelligence. The EO-1 science analysis software is defined as one of the “controlling systems” in IDEA. In the IDEA architecture, a communications wrapper is used to send messages between the agents, similar to the software bus in EO-1. In the description of IDEA there is no information about the deployment of IDEA to any domains, so a comparison of the performance or capabilities is not possible at this time. In many ways IDEA represents a more AI-centric architecture with declarative modeling at its core and ASE represents more of an evolutionary engineered solution.

ASE was originally scheduled for flight on the Techsat-21 mission [Chien et al. 2002]. However this mission was cancelled and the software was adapted for flight on EO-1. The principal changes from the Techsat-21 to EO-1 are that the science payload was changed from a synthetic aperture radar (SAR) to a hyperspectral imaging device (Hyperion). This change requires significant alteration to the science targets and analysis algorithms. The basic software architecture and components (e.g. CASPER and SCL) have remained the same.

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 will lead to a reduction in data downlink. In addition, the ASE will increase 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.

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