Next Generation Autonomous Operations on a Current Generation Satellite

Rob Sherwood, Steve Chien, Daniel Tran, Benjamin Cichy, Rebecca Castano, Ashley Davies, Gregg Rabideau,
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
Firstname.Lastname@jpl.nasa.gov

ABSTRACT

The Autonomous Sciencecraft Experiment (ASE) will fly onboard the Earth Orbiter 1 mission in 2003. ASE uses onboard continuous planning, robust task and goal-based execution, and onboard machine learning and pattern recognition to radically increase science return by enabling intelligent downlink selection and autonomous retargeting. In this paper we discuss how these AI technologies are synergistically integrated in multi-layer control architecture to enable a virtual spacecraft science agent. This software will demonstrate the potential for future space missions to use onboard decision-making to detect science events and respond autonomously to capture short-lived science events and to downlink only the highest value science data. As a result, ground-based mission planning and analysis functions will be simplified, thus reducing operations cost.

1. INTRODUCTION

In 2003, the ASE flying on the EO-1 spacecraft will demonstrate several integrated autonomy technologies to enable autonomous science. Several science algorithms including: onboard event detection, feature detection, change detection, and unusualness detection will be used to analyze science data. These algorithms will be used to downlink science data only on change, and will detect features of scientific interest such as volcanic eruptions, sand dune migration, growth and retreat of ice caps, cloud detection, and crust deformation. These onboard science algorithms are inputs to onboard decision-making algorithms to modify the spacecraft observation plan to capture high value science events. This new observation plan will 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 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 will 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 editing
- *Robust execution management software* using the Spacecraft Command Language (SCL) [10] package to enable event-driven processing and low-level autonomy
- The Continuous Activity Planning, Scheduling, and Replanning (CASPER) [5] *planner* that will replan activities, including downlink, based on science observations in the previous orbit cycles

The onboard science algorithms will analyze the images to extract static features and detect changes relative to previous observations. Prototype software has already been demonstrated on EO-1 Hyperion data to automatically identify regions of interest including regions of change (such as flooding, ice melt, and lava flows). Such onboard science will enable retargeting and search, e.g., retargeting the instrument on a subsequent orbit cycle to identify and capture the full extent of a flood. On future interplanetary space missions, onboard science analysis will enable capture of short-lived science phenomena at the finest time-scales without overwhelming onboard caching or downlink capacities. Examples 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) will generate mission operations plans from goals provided by the onboard science analysis module. The model-based planning algorithms will enable rapid response to a wide range of operations scenarios based on a deep model of spacecraft constraints, including faster recovery from spacecraft anomalies. The onboard planner will accept as inputs the science and engineering goals and ensure high-level goal-oriented behavior for the constellation.

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.

A typical ASE demonstration scenario involves monitoring of active volcano regions such as Mt. Etna in Italy. (See **Error! Reference source not found.**) Hyperion data have been used in ground-based analysis to study this phenomenon. The ASE concept would be applied 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 IR and near IR bands are used.
3. During execution of this plan, the EO1 spacecraft images Mt. Etna with the Hyperion instrument.
4. The *Onboard Science Software* analyzes the image and detects a fresh lava flow. Based on this detection the image is downlinked. Had no new lava flow been detected, the science software would generate a goal for the planner to acquire the next highest priority target in the list of targets. (See Figure 1.) The addition of this goal to the current goal set triggers CASPER to modify the current operations plan to include numerous new activities in order to enable the new science observation.
5. The SCL software executes the CASPER generated plans in conjunction with several autonomy elements.
6. This cycle is then repeated on subsequent observations.

2. THE EO-1 MISSION

Earth Observing-1 (EO-1) is the first satellite in NASA's New Millennium Program Earth Observing series. 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.

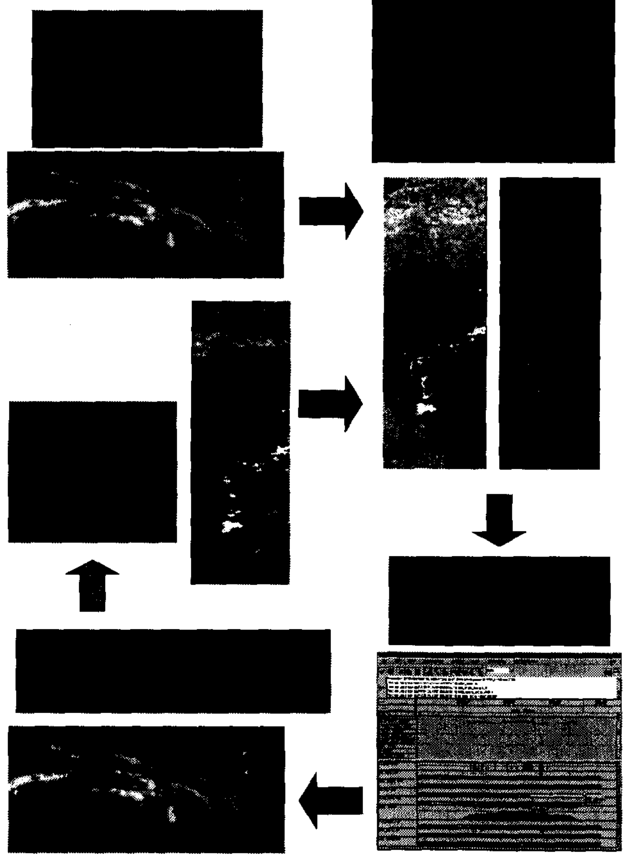

Figure 1: Autonomous Science Mission Concept

For each scene, over 20-Gbits of scene data from the Advanced Land Imager (ALI), Hyperion, and Atmospheric Corrector (AC) are collected and stored on the onboard solid-state data recorder (WARP) at high rates.

EO-1 is currently in extended mission, having more than achieved its original technology validation goals. As an example, over 5,000 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 (although investigations are underway to determine feasibility of analyzing ALI data onboard in follow-on experiments). The Hyperion is a high-resolution hyper spectral imager capable of resolving 220 spectral bands (from 0.4 to 2.5 μm) 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 – one for command and data handling functions and the other 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 autonomy software operates on the WARP M5.

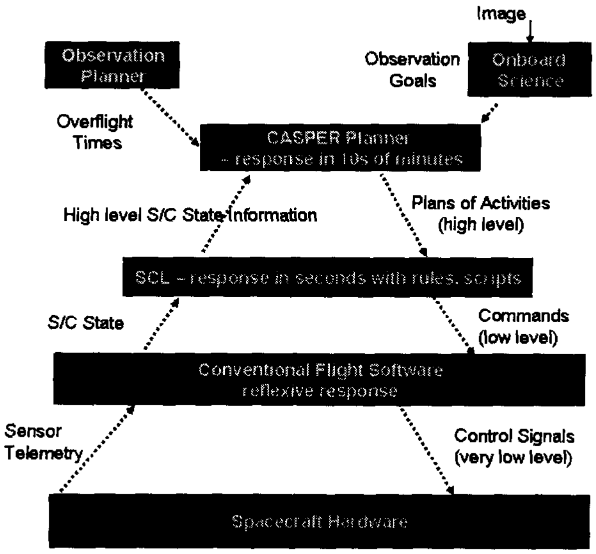

Figure 2: Autonomy Software Architecture

3. AUTONOMY SOFTWARE ARCHITECTURE

The autonomy software on EO-1 is organized into a traditional three-layer architecture (See Figure 2.). At the highest level of abstraction, the Continuous Activity Scheduling Planning Execution and Replanning (CASPER) system is responsible for mission planning functions. CASPER schedules science activities while respecting spacecraft operations and resource constraints. CASPER operates on the tens of minute's timescale. CASPER scheduled activities are inputs to the Spacecraft Command Language (SCL) system, which is responsible for 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 FSW 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.

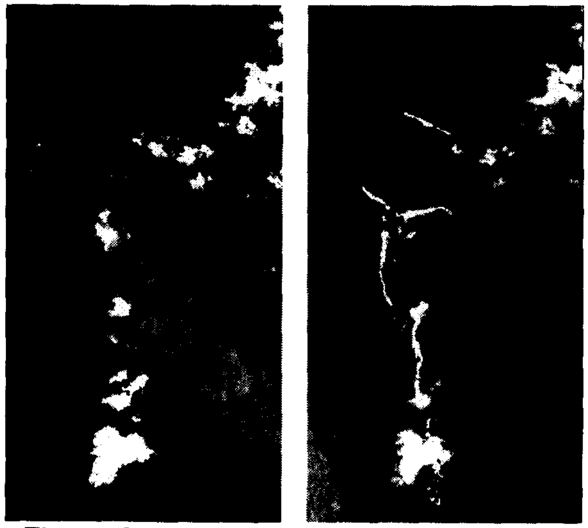

Figure 3: Thermal Anomalies associated with volcano activity at Mt. Etna, visual spectra at left and Infra-red at right.

4. ONBOARD SCIENCE ANALYSIS

The first step in the autonomous science decision cycle is detection of science events of interest. In the complete experiment, a number of science analysis technologies will be flown including:

- Thermal anomaly detection – uses infrared spectra peaks to detect lava flows and other volcanic activity. (See Figure 3.)
- Cloud detection – uses intensities at six different spectra and thresholds to identify likely clouds in scenes. (See Figure 4.)
- Flood scene classification – uses ratios at several spectra to identify signatures of water inundation as well as vegetation changes caused by flooding.
- Change detection – uses potentially 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 Figures 5 and 6.)
- Generalized Feature detection (Discovery) – uses trainable recognizers to detect such features as sand dunes and wind streaks.

- Anomaly detection – uses Gabor filters to classify the data and selects outliers to return as higher probability of science interest [2].

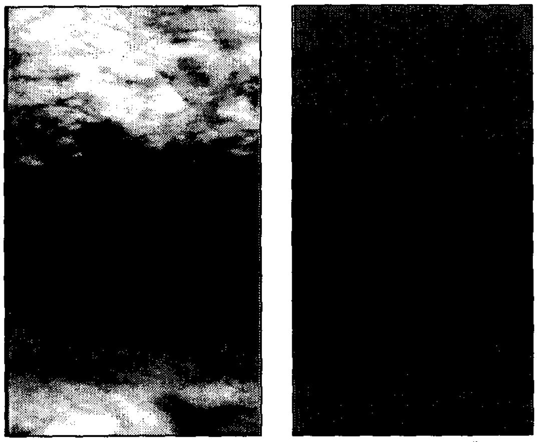

Figure 4: Cloud Detection of a Hyperion Scene – visual image at left, grey in the image at right indicates detected cloud.

The first series of experiments will demonstrate use of thermal anomaly detection techniques to detect sites of active volcanism. Initial experiments will also use the cloud detection triggers. In the event of high cloud cover, data collections will be rescheduled. These techniques have been scheduled first because of the maturity and simplicity of the algorithms.

Later flights will validate as many science analysis algorithms as resources allow. These flights will begin by validating change detection on multiple science phenomena, feature detection on Aeolian (wind) features such as sand dunes, sand shapes, and wind streaks, and the Discovery algorithm. Validating this portfolio of science algorithms will represent a valuable step forward to enabling future autonomous science missions [6].

5. 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 spacecraft and mission constraints. The CASPER [5] 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 [15] 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.

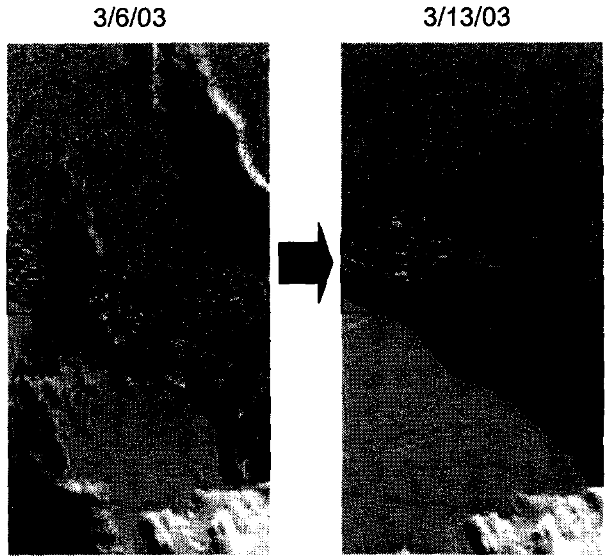

Figure 5: Change Detection Scenes indicating Ice Breakup in the Larsen Ice Shelf, Antarctica. Advanced Land Imager Data, red box indicates detailed Hyperion scene.

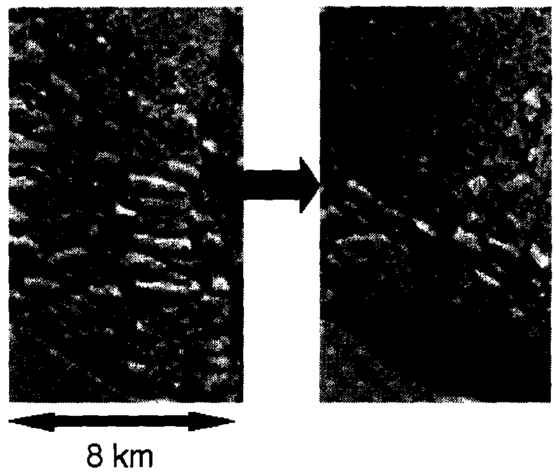

Figure 6: Detailed Hyperion scene indicating change on Larsen Ice Shelf.

CASPER is responsible for long-term 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, CASPER plans a response. This event may warrant a high priority request for a subsequent image of the target to study the evolving phenomena. In this case, CASPER will modify 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.

In the context of ASE, CASPER reasons about the majority of spacecraft operations constraints directly in its modeling language. However, there are a few notable exceptions. First, the over flight constraints are calculated using ground-based orbit analysis tools. The over flight opportunities and pointing required for all targets of interest are uploaded as a table and utilized by CASPER to plan. Second, the ground operations team will initially perform management of the momentum of the reaction wheels for the EO-1 spacecraft. This is because of the complexity of the momentum management process caused by the EO-1 configuration of three reaction wheels rather than four. In the proposed follow-on experiment we will examine the possibility of migrating this function onboard.

6. ONBOARD ROBUST EXECUTION

ASE uses the Spacecraft Command Language (SCL) [10] 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 allows the distribution of notification and request messages to integrate SCL with other onboard software. This design enables either 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 will also be 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 with a messaging system.

Many aspects of autonomy are implemented in SCL. For example, many constraint checks redundant with fault protection are implemented in SCL. Before each command is sent from the autonomy software to the C&DH software by SCL, it undergoes a series of constraint checks to ensure that it is a valid command. Any pre-requisite states required by the command are checked (such as the communications system being in the correct mode to accept a command). SCL will also verify that there is sufficient power so that the command does not trigger a Low Bus Voltage and that there is sufficient energy in the battery so as to retain safe margins. Using SCL to check these constraints (while included in the CASPER model) provides an additional level of safety to the autonomy FSW.

7. FLIGHT STATUS

The ASE software was integrated under the flight version of VxWorks in December 2002, and has been undergoing testing and integration with the WARP flight software. Based on the results of this testing, the ASE software is planned for upload in July 2003. for approximately one month of shadow operations to provide additional confidence. At the successful completion of this period and patching of any discovered issues, a baseline of 425 experiment observations will be acquired. This experiment phase should complete by May 2004. At this point a decision will be made to use ASE as part of the baseline EO1 mission operations.

9. CONTRIBUTION TO FUTURE MISSIONS

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

As described above, the ASE will monitor selected terrestrial environmental processes that directly impact human existence, but which, importantly, have extraterrestrial analogues. Onboard science data processing has been identified by the NASA Space Science Technology Steering Group as an enabling technology for several Exploration of the Solar System (ESS) missions including Europa Orbiter (EO), Pluto Express (PE), Neptune Orbiter (NO), and Saturn Ring Observer (SRO). Specifically, the feature tracking and feature recognition technologies to be demonstrated through this report are considered highly enabling to these missions. In addition, eight Sun-Earth Connection (SEC) missions (GEC, ISP, MC, MMS, RAM, RBM, PASO, SN) and three Structure and Evolution of the Universe missions (ARISE, CON-X, OWL) have identified the need for this technology.

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:*

- Monitor surface change as function of changing tidal stress field
- Monitor areas of greatest tidal stresses
- Search for surface change, that is, evidence of recent activity
- Search for landing sites that have a high probability of lander survivability and where the crust is thin enough for deployment of a sub-crust submarine explorer

Mars is the target of a series of missions by NASA and other space agencies. These missions are summarized in Table 1. An imaging orbiter mission could monitor ice cap change, search for wind streaks, and changes in dune fields, as well as search for water-related change, such as mass-wasting and debris flow processes [11]. Of particular importance is the task of landing site selection. Selection algorithms can be pre-tested on terrestrial analogs. Also interesting is the gradual construction of Mars Network, which will yield a GPS capability. This would allow a low-cost second deployment to Mars of a variable-baseline interferometer SAR constellation.

Launch Year	Mission
2001	Mars Odyssey
2003	Mars Exploration Rovers Mars Express Orbiter (ESA) Nozomi (ISAS, 2003 arrival)
2005	Mars Reconnaissance Orbiter
2007	Competed Scout mission
2008	Mars TelecomSat
2009	Mars Science Laboratory SAR-capable science orbiter
2011+	Sample return mission

Table 1. Summary of Relevant Mars Missions

A robot outpost on Mars has been proposed to pave the way for human exploration. The outpost may consist of a hundred rovers, functioning as a robot colony. Such an undertaking, with a wide range of rovers both on and above the surface, will by its nature need to operate autonomously. The massive amount of data generated will need autonomous processing to extract science content, which will in part be used to determine subsequent colony operations. ASE is a step on the road to achieving this level of autonomy.

The ASE Team has identified the NASA Mars Program as an ideal candidate for technology infusion of the ASE software. As a result, we have been working closely with the Mars Odyssey Project to identify and ground test science analysis algorithms that could be used for discovery of interesting science on Mars. The goal of this work is to have a existing or future Mars mission infuse the ASE software into their baseline flight software.

9. IMPACT ON OPERATIONS

ASE can impact several aspects of spacecraft operations. The mission planning process is simplified because the operation team no longer has to build detailed sequences of commands. The spacecraft can be commanded using high-level goals, which are then detailed by the planner onboard. The processes of planning, build sequence, upload sequence, execute sequence, downlink data, analyze data, and build new sequence are entirely automated using ASE. For example, in the current EO1 operations, a significant percentage of the images downlinked are of no value because they are mostly covered in clouds. Using ASE, these images can now be discarded onboard and the satellite can acquire another image of a different area. This saves time and labor for the mission planning team, science analysis team, ground station team, flight operations team, and data processing and archive team.

Due to computing limitations, the ASE architecture for EO1 does not include an autonomous fault protection component. Although this wasn't included for EO1, it's a natural fit for the ASE onboard autonomy software. In one example, CASPER generates a mission level plan that includes a sequence of behavior goals, such as producing thrust. The SCL executive is responsible for reducing these goals to a control sequence, for example, opening the relevant set of valves leading to a main engine. A device, such as a valve, is commanded indirectly; hence, SCL must ensure that the components along the control path to the device are healthy and operating before commanding that device. Components may be faulty, and redundant options for achieving a goal may exist; hence, SCL must ascertain the health state of components, determine repair options when viable, and select a course of action among the space of redundant options. Adding this level of fault protection autonomy to a future mission could in theory, eliminate the spacecraft analysis team. The team would no longer be required to monitor the spacecraft health because that would be done onboard using *model-based mode estimation and mode reconfiguration.* [16] The team would also not be required to respond to "safe-hold" periods because anomalies would be handled and reconfigured onboard. Using this software requires a greater up front investment in building the spacecraft models, but much of the underlying software has already been developed in research efforts.

Using the onboard science analysis software can also save time and labor for the science team. The feature detection algorithms can identify specific features of interest within the images. The spacecraft can then downlink the entire image when features are detected, only the detected features, or even a summary of the detected features. Scientists no longer have to analyze many different images to find a feature of interest. In fact, images that do not contain features of interest do no even have to be downlinked. These algorithms can be particularly useful on bandwidth-limited missions by returning the most important science data.

10. CONCLUDING REMARKS

In 1999, the Remote Agent experiment (RAX) [13] executed for a few days onboard the NASA Deep Space One mission. RAX is an example of a classic three-tiered architecture [8], as is the EO-1 experiment. RAX demonstrated a batch onboard planning capability (as opposed to EO-1's continuous planning) and RAX did not demonstrate onboard science. PROBA [14] is a European Space Agency (ESA) mission that will be demonstrating 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 [3]. The 3CS mission was scheduled for launch in late 2003. However as it was scheduled for launch in the Space Shuttle, it has been delayed indefinitely. 3CS will use 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 [12]. 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.

ASE on EO-1 will demonstrate an integrated autonomous mission using onboard science analysis, replanning, and robust execution. EO-1 will perform intelligent science data selection that will lead to a reduction in data downlink. In addition, the EO-1 experiment 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 cost.

11. ACKNOWLEDGEMENT

Portions of this work were performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. We would like to acknowledge the important contributions of Nghia Tang and Michael Burl of JPL, Dan Mandl, Stuart Frye, Seth Shulman, and Stephen Ungar of GSFC, Jerry Hengemihle and Bruce Trout of Microtel LLC, Jeff D'Agostino of the Hammers Corp., Robert Bote of Honeywell Corp., Jim Van Gaasbeck and Darrell Boyer of ICS, Michael Griffin and Hsiao-hua Burke of MIT Lincoln Labs, Ronald Greeley, Thomas Doggett, and Kevin Williams of ASU, and Victor Baker and James Dohm of University of Arizona.

12. REFERENCES

[1] M.C. Burl, L. Asker, P. Smyth, U. Fayyad, P. Perona, J. Aubele, and L. Crumpler, "Learning to Recognize Volcanoes on Venus," *Machine Learning Journal,* April 1998.

[2] M.C. Burl and D. Lucchetti, "Autonomous Visual Discovery", *SPIE Aerosense Conference on Data Mining and Knowledge Discovery,* (Orlando, FL), April 2000.

[3] S. Chien, B. Engelhardt, R. Knight, G. Rabideau, R. Sherwood, E. Hansen, A. Ortiviz, C. Wilklow, S. Wichman , "Onboard Autonomy on the Three

Corner Sat Mission," Proc i-SAIRAS 2001, Montreal, Canada, June 2001.

[4] S. Chien, R. Sherwood, M. Burl, R. Knight, G. Rabideau, B. Engelhardt, A. Davies, P. Zetocha, R. Wainright, P. Klupar, P. Cappelaere, D. Surka, B. Williams, R. Greeley, V. Baker, J. Doan, "The TechSat 21 Autonomous Sciencecraft Constellation", Proc i-SAIRAS 2001, Montreal, Canada, June 2001.

[5] S. Chien, R. Knight, A. Stechert, R. Sherwood, and G. Rabideau, "Using Iterative Repair to Improve Responsiveness of Planning and Scheduling," *Proceedings of the Fifth International Conference on Artificial Intelligence Planning and Scheduling*, Breckenridge, CO, April 2000. (also casper.jpl.nasa.gov)

[6] A.G. Davies, R. Greeley, K. Williams, V. Baker, J. Dohm, M. Burl, E. Mjolsness, R. Castano, T. Stough, J. Roden, S. Chien, R. Sherwood, "ASC Science Report," August 2001. (downloadable from ase.jpl.nasa.gov)

[7] Davies, A. G., E.D. Mjolsness, A.G. Gray, T.F. Mann, R. Castano, T.A. Estlin and R.S. Saunders (1999) Hypothesis-driven active data analysis of geological phenomena using semi-autonomous rovers: exploring simulations of Martian hydrothermal deposits. *EOS, Trans. Amer. Geophys. Union,* 80, no. 17, S210.

[8] E. Gat et al., Three-Layer Architectures. in D. Kortenkamp et al. eds. *AI and Mobile Robots*. AAAI Press, 1998.

[9] Goddard Space Flight Center, EO-1 Mission page: http://eo1.gsfc.nasa.gov

[10] Interface and Control Systems, SCL Home Page, sclrules.com

[11] M. C. Malin and K. S. Edgett, "Evidence for recent groundwater seepage and surface runoff on Mars," *Science*, 288, 2330-2335, 2000.

[12] N. Muscettola, G. Dorais, C. Fry, R. Levinson, and C. Plaunt, "IDEA: Planning at the Core of Autonomous Reactive Agents," Proceedings of the Workshops at the AIPS-2002 Conference, Tolouse, France, April 2002.

[13] NASA Ames, Remote Agent Experiment Home Page, http://ic.arc.nasa.gov/projects/remote-agent/.

[14] The PROBA Onboard Autonomy Platform, http://www.estec.esa.nl/proba/

[15] G. Rabideau, R. Knight, S. Chien, A. Fukunaga, A. Govindjee, "Iterative Repair Planning for Spacecraft Operations in the ASPEN System," *International Symposium on Artificial Intelligence Robotics and Automation in Space*, Noordwijk, The Netherlands, June 1999.

[16] B.C. Williams and P.P. Nayak, "A Reactive Planner for a Model-based Executive," *Proc. International Joint Conference on Artificial Intelligence*, Nagoya, Japan, 1997.