Mission Operations with Autonomy: A preliminary report for Earth Observing-1

Gregg Rabideau, Steve Chien, Rob Sherwood, Daniel Tran, Benjamin Cichy

Jet Propulsion Laboratory, California Institute of Technology

firstname.lastname@jpl.nasa.gov

Dan Mandl, Stuart Frye[1], Seth Shulman[2], Robert Bote[2], Joseph Szwaczkowski[2]

Goddard Space Flight Center

firstname.lastname@gsfc.nasa.gov

Darrell Boyer, Jim Van Gaasbeck

Interface & Control Systems

{dboyer, jimv}@interfacecontrol.com

Abstract. Space mission operations are extremely labor and knowledge-intensive and are driven by the ground and flight systems. Inclusion of an autonomy capability can have dramatic effects on mission operations. We describe the current (more conventional) mission operations flow for the Earth Observing-1 (EO-1) spacecraft as well as the more autonomous operations to which we are transitioning as part of the Autonomous Sciencecraft Experiment (ASE).

1 Introduction

EO-1 is the first satellite of the Earth observing series of NASA's New Millennium Program (NMP). Since its launch on November 21, 2000, under management of the Goddard Space Flight Center (GSFC), EO-1 has demonstrated many new technologies for space-based Earth observing satellites. These technologies include several advanced instruments for collecting multispectral and hyperspectral images, and a high-rate, high-volume solid state recorder (SSR) for storing the images. The EO-1 spacecraft is in a low-Earth orbit that follows 1 minute behind the Landsat-7 spacecraft in the AM constellation. This formation flying allows scientists to take coordinated pairs of images from the different instruments on both satellites.

As a part of the NMP Space Technology-6 (ST-6) project, the Autonomous Sciencecraft Experiment (ASE) was selected to demonstrate advanced concepts in flight software. ASE is a set of integrated technologies for autonomously collecting, processing and downlinking science data. These components include: onboard science analysis, onboard mission planning, and onboard robust execution. First, several different science algorithms are used to analyze science data onboard. These algorithms process the image to detect the presence of unique features in the image, such as clouds, flooding, ice formation, or volcanic activity. The detection of these features is used as a trigger to automatically submit requests for additional data. Next, these requests are serviced by the onboard planner, CASPER. CASPER processes the requests into a more detailed sequence of future spacecraft activities that is consistent with the extensive list of spacecraft and mission constraints. Finally, when an activity is imminent, CASPER submits a request for execution by the onboard executive, SCL. SCL initiates a set of scripts that perform the complete sequence of commands for the spacecraft and its payloads. Prior to executing each command, constraints are checked again to confirm the validity of the command as well as ensure the safety of the spacecraft. After the command is sent, the executive checks for a successful initiation and completion of the command. When a full sequence for a data collection is complete, one or more of the science processing algorithms are triggered and the entire process repeats.

The ASE software provides many benefits to the science and engineering teams involved in operations. First, the onboard science algorithms can prioritize the data before it is sent to Earth. These priorities can then be used to increase science return by maximizing a spacecrafts limited resources. For example, if clouds are detected in an image, this image can be removed from the onboard recorder and from the downlink queue, freeing up these

[1] MitreTek
[2] Honeywell

resources for higher quality data. Ultimately, this also results in fewer “junk” images that must be examined by the science team. The automated planning system, CASPER, also has several benefits. Scientists can use it as a ground planner to select a consistent set of high priority observations from the full set of inconsistent target requests. When done manually, this task can be tedious and require extensive knowledge of spacecraft constraints. The same system can be used for onboard planning. This not only reduces the inputs required by the flight system (only the goals need to be uplinked, rather than the full command sequences) but also enables faster re-planning responses to either engineering anomalies or changes in science priorities. Finally, the SCL onboard executive provides several benefits over traditional sequencing. By monitoring commands and spacecraft state, the executive can make quick changes to the more immediate parts of the sequence. This can help ensure the success of the sequence, and possibly optimize its execution.

In the fall of 2002, the ASE team at JPL joined efforts with the EO-1 team at GSFC to demonstrate this advanced flight software system. The purpose of this demonstration is to validate the feasibility and the benefits of using autonomy software. In the following sections we will describe in more detail the EO-1 spacecraft, the ASE software, and the new way of operating a mission that takes advantage of autonomy software.

2 The EO-1 Spacecraft

The EO-1 spacecraft [1] is in an approximately 90 minute, 705 Km sunsynchronous (98° inclination) orbit around the Earth. It has two main instruments for collecting science data. The Advanced Land Imager (ALI) is an advanced spectrometer with 30-meter resolution for multispectral pixels and 10 meter resolution for panchromatic pixels. The ALI generates data at a rate of about 102 megabits per second (102 Mbps). The Hyperion is a hyperspectral imager (HSI) that is capable of resolving 220 spectral bands from 0.4 to 2.5 µm with a 30 meter spatial resolution. The HSI generates data a rate of about 233 Mbps. A typical scene collects about 16 seconds of data including calibrations, so together the two instruments generate about 5 gigabits of data for each scene.

To store the images, EO-1 carries the Wideband Advanced Recorder Processor (WARP). The WARP is a 45 gigabit, high-rate SSR that is capable of storing about nine high resolution images. The spacecraft has several communication antennae. Mainly for engineering data, there are two omni-directional, S-band antennae that typically downlink at a rate of 2 Mbps. The S-band antennae are mounted on opposite sides of the spacecraft to allow contact at any orientation. For the large volumes of science data, there is a high-rate, electronically steerable, phased-array, X-band antenna with a 105 Mbps downlink rate.

The EO-1 attitude control system (ACS) is used to point the spacecraft at the various targets. Reaction wheels are used to rotate the spacecraft and stabilize all three axes to a 0.03° pointing accuracy. Torque rods are used to desaturate, or bias the wheel speed. EO-1 also has a hydrazine propulsion system for correcting errors in orbit insertion, orbit maintenance, formation flying, and eventually for de-orbit.

EO-1 is carrying two Mongoose V R3000 12 MHz radiation-hardened flight processors with 256 MB of RAM each. The primary CPU is used for Command and Data Handling (C&DH). The WARP uses the second CPU for data recording, processing and playback. To reduce risk and avoid contention for cycles on the primary C&DH processor, the ASE software runs on the WARP processor.

3 ASE

The ASE onboard flight software includes several autonomy software components (See Figure 1):

- 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 masking [2]
- Robust execution management software using the Spacecraft Command Language (SCL) [3] package to enable event-driven processing and low-level autonomy
- The Continuous Activity Scheduling Planning Execution and Replanning (CASPER) [4] software 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 land, ice, snow, water, and thermally hot areas. Repeat imagery using these algorithms can detect regions of change (such as flooding and ice melt) as well as regions of activity (such as lava flows). Using these algorithms onboard 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. These can be captured at the finest time-scales without overwhelming onboard memory or downlink capacities by varying the data collection rate on the fly. 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 and resurfacing on Europa.

Responsible for long-term mission planning, the ASE planner (CASPER) will accept as inputs the science and engineering goals and ensure high-level goal-oriented behavior. These goals may be provided by either the ground operators or triggered by the onboard science algorithms. 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. CASPER uses repair-based techniques [5] that allow the planner to make rapid changes to the current plan to accommodate the continuously changing spacecraft state and science requests. During repair, CASPER collects a set of conflicts that represent violations of spacecraft constraints. Generic algorithms are used to select and analyze a conflict to produce a set of potential plan modifications that may resolve the conflict. Heuristics are used to select a potential modification, and the plan is updated and reevaluated for new conflicts. This process continues until no conflicts remain.

The robust execution system (SCL) is a software package that integrates procedural programming with a real-time, forward-chaining, rule-based system. SCL accepts the

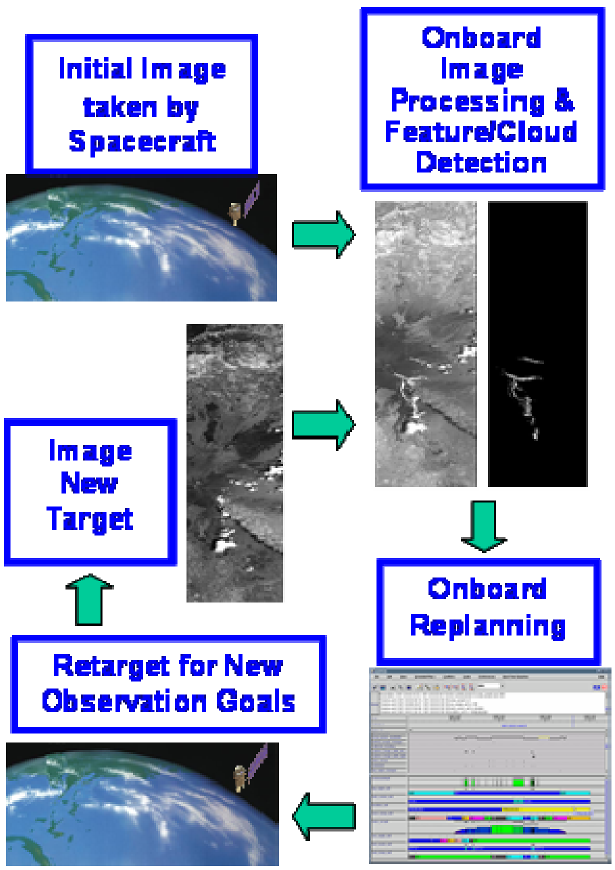

Figure 1: ASE

CASPER-derived activities as an input and executes the activities as scripts of low-level commands. Immediately before sending each command, the various constraints on the command are checked with the current spacecraft state. SCL uses a rule-based system to monitor spacecraft health and safety during the execution of the activities. When a safety risk is identified, SCL makes on-the-fly changes to the short-term plan to avoid potentially hazardous states or commands. SCL also 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 scenario involves monitoring of active volcano regions such as Mt. Etna in Italy. (See Figure 2) Hyperion data have been used in ground-based analysis to study this phenomenon. The ASE concept will 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 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.

4 Current EO-1 Operations

The EO-1 spacecraft is currently operated [6] 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) is 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 is similar to the Microwave Anisotropy Probe (MAP) [7] systems. Figure 2 shows the general operations flow.

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

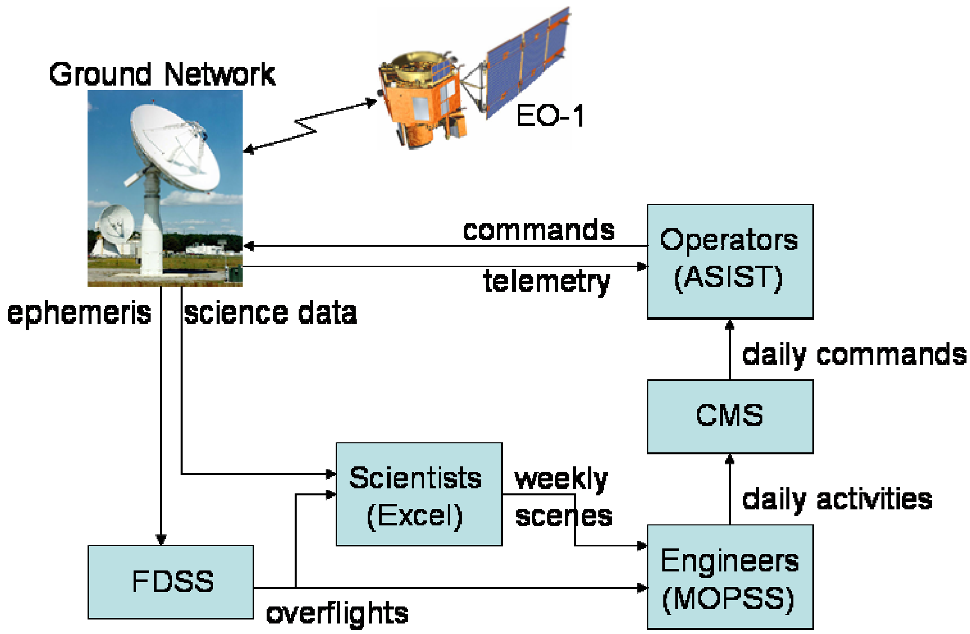

Figure 2: Current Operations

4.1 Weekly Operations

The U. S. Geological Survey (USGS) manages 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 will be visible for the upcoming week, including the orbits in which they will 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 allows the engineer to calculate approximate overflight times for potential science targets and ground station contacts.

Many targets are visible in any given orbit, but only about one to two images can be taken due to operations constraints. Therefore, scenes for a given week must be selected from the list of potential scenes. Scene priorities are based on several factors including: who made the request, if it was paid for, and if it involves a fleeting science event. The EO-1 science and engineering teams meet weekly with a USGS representative to verify the selected requests and to make minor modifications to the plan for the following week.

After collecting several scenes, the WARP will reach capacity and commands must be scheduled to free up space for new requests. Before this can be 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 overfilling.

4.2 Daily Operations

After the weekly science meeting, the mission planner uses MOPSS to begin scheduling the 1-week set of activities. First, spacecraft maneuver commands must be 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, 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 desaturate 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 selection of activities is 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 must 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 delivered 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.

5 EO-1 Operations with ASE

The Autonomous Sciencecraft Experiment (ASE) team is working on advanced software for the EO-1 mission. Much of this software can be used both on ground workstations for mission operations and on the flight processor for autonomous operations. In this section, we will discuss the impact of this software on the weekly and daily operations of EO-1. Table 1 compares the current operations with modified steps that include ASE. Some of the discussion (steps 5-8) will focus on proposed work for reducing the cost of operating EO-1. The remaining (steps 9-15) will describe funded and ongoing work for the New Millennium Program.

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

Table 1

5.1 Weekly Operations

The first four steps do not change with the introduction of the ASE ground and flight software. However, ASE needs the results of these calculations for planning purposes.

For the weekly science planning, some of the ASE software can be 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. The CASPER planning software can be used to select the highest priority targets that comply with spacecraft constraints such as power and thermal requirements. Initial selection can be done on the ground while re-prioritization can be done in flight.

CASPER can also be used to schedule downlinks for the observations. The GN schedule would be input to identify the X-band downlink opportunities. The planner would use its model of the WARP to predict when the memory will reach capacity. Using this model, it can automatically add 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 overflights and spacecraft constraints. Again, initial downlink schedules can be generated on the ground with re-planning done in flight.

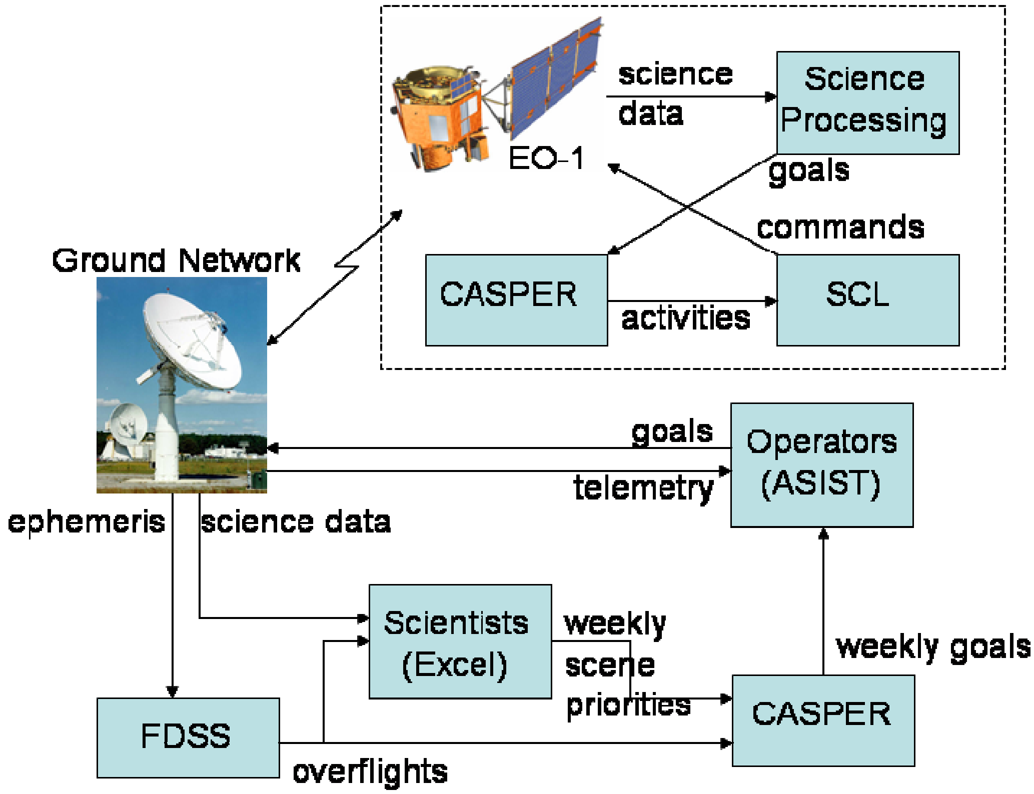

Figure 3: Modified Operations

Finally, the CASPER planner will be interfaced with the Dynamics Support System (FDSS). The planner will generate the required maneuver and wheel bias commands while the flight dynamics software will use the 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.

5.2 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.

6 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.

7 Flight Tests of ASE

To date, we have successfully performed several in-flight demonstrations of CASPER's ability to schedule detailed command sequences from high-level goals. In the near future, we will be delivering a new release of ASE that will also perform onboard science analysis and re-planning. Also, because the focus of ASE is on advanced *flight* software, many of the ground system capabilities have not been demonstrated. We have not yet, for example, shown CASPER's ability to automatically select an optimal set of science targets or to create the set of requested downlinks. However, following the flight tests, we anticipate continuing work to increase the automation in the ground system.

Initial flight tests were conservative, and layers of autonomy were added incrementally as confidence in the software was established. First, the ASE software was run on a ground workstation with a simulation of activities for an upcoming orbit. During this simulation, flight software commands were captured as they were issued by ASE. These commands were then inserted into the uplink sequence of commands for the day that included the chosen orbit. During several tests in July of 2003, ASE-generated commands were executed in flight without issue using the original EO-1 flight software, adding confidence in the ability of the ASE software to generate the appropriate sequence.

After a few of these tests, and more testing on various flight testbeds, we uploaded the ASE software and performed tests on the spacecraft. In preparation of the flight software tests, we developed a set of procedures for the operators. These procedures include:

- Uploading the new code
- Starting the new code
- Starting SCL
- Starting CASPER
- Uploading files into the RAM disk
- Downloading files from the RAM disk
- Loading files from the RAM disk into CASPER
- Enabling ASE Telemetry
- Enabling ASE Commanding
- Restarting the original code

The first layer tested was the interface between ASE and the original EO-1 flight software. This task acts as a communication bridge, routing commands and telemetry between the two core systems. Without running CASPER or SCL, the bridge software was started onboard and simple commands were issued while monitoring specific telemetry during ground contacts. These tests were completed in May, 2003.

With the bridge interface working, the next layer to test was robust execution with SCL. Again, ground contacts were established to start and monitor various tests, this time to demonstrate that SCL could safely send commands and receive telemetry. These tests were completed in May, 2003.

Next, we tested CASPER and SCL integrated to generate and execute sequences of commands. During a series of ground contacts scheduled for the test day, the ASE software was started, the bridge was enabled, the goal file was loaded onto the RAM disk and into CASPER, and the planning and execution were monitored. For the first few tests in October of 2003, we executed simple goals that expanded into only a few commands. Later, we tested a more complicated sequence that performed an image calibration for the Hyperion instrument. Eventually, the software correctly generated and executed a set of goals to:

- Bias the momentum wheels
- Slew the spacecraft
- Collect image data for the scene
- Slew back to nadir
- Desaturate the wheels
- Downlink the image
- Erase the image from the WARP

Because this scenario takes several hours, and ground contacts are typically around 10 minutes long, much of the execution could not be monitored. We started by monitoring the critical section that collects data, and later executed the entire sequence “in the blind.” These tests were completed in January, 2004.

Finally, at the time of this writing, we are making preparations to perform a flight test of the full integrated system within the next few months. This demonstration will include:

- CASPER generating the initial plan
- SCL executing the initial plan
- Science algorithms analyzing the data (detecting clouds [8], lava, etc.)
- Science algorithms making new requests based on the analysis
- CASPER re-planning to include the new requests
- SCL executing the new plan (including the new request)

8 Monitoring ASE Performance

To monitor the tests, we developed a set of telemetry points for each of the ASE modules. This is typically high-priority heath and status data that will be continuously saved to the onboard recorder and downlinked during ground contacts. The real-time engineering data for EO-1 is monitored with the ASIST ground software tool developed at GSFC (see Figure 4).

Because the bridge acts as a gateway, it has several telemetry points to verify that we have enabled or

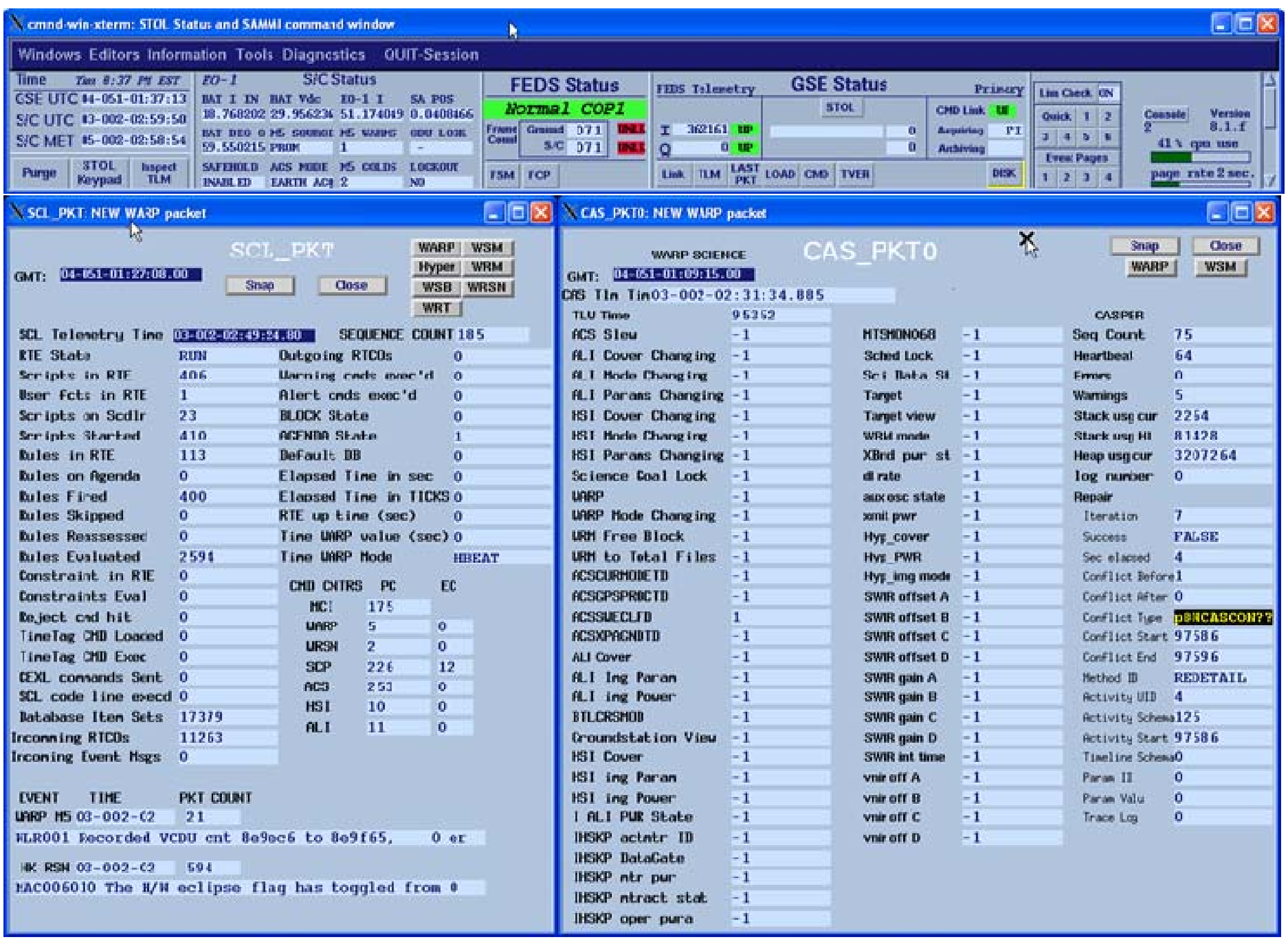

Figure 4: ASIST Workstation with SCL and CASPER Monitoring Data

disabled the flow of spacecraft commands and telemetry. It also has command counters for those issued to the ASE software. SCL provides telemetry on its state including counters for the number of scripts executed. CASPER provides statistics on the planning algorithm including the types of conflicts that it addresses and what changes it makes to the plan when repairing the conflicts. It also generates telemetry that identifies any differences it finds between the actual spacecraft state and the state it expects during the execution of the plan.

Each software module also saves more detailed data to log files that are stored on a RAM disk. At the end of each test, these log files are downlinked either to debug new issues or to further validate the success of the test.

9 Summary

The Autonomous Sciencecraft Experiment (ASE) team is working on advanced software for EO-1 mission. This software can be used both on ground workstations and on the flight processor to provide an increased level of autonomy. The ground planner can be used to reduce the workload involved in generating long-term plans. The onboard ASE software provides a high-level goal-oriented system that is capable of identifying and rapidly responding to several different types of science events. This advanced software suite is being demonstrated as a means of validating the algorithms for future NASA missions.

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