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Autonomous Mission Operations: Using Earth Observing One as a Sensor Web Testbed

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The Earth Observing One satellite is being used along with a variety of ground and flight software, other satellites, and ground sensors to prototype a sensor web.

Inside Track

A series of ongoing experiments are being conducted at the NASA Goddard Space Flight Center to explore integrated ground and space-based software architectures that enable sensor webs.

A sensor web is a coherent set of distributed nodes interconnected by a communications fabric that collectively behave as a single, dynamically adaptive, observing system.

The nodes can be comprised of satellites, ground instruments, computing nodes etc. Sensor web capability requires autonomous management of constellation resources.

This becomes progressively more important as more and more satellites share resources, such as communication channels and ground stations while automatically coordinating their activities.

This activity allowed us to explore the difficulties that occur in the assembly of sensor webs given today's technology.

We will present an overview of the software system architecture, some key experiments, and lessons learned to facilitate better sensor webs in the future.

1 Introduction

At NASA/Goddard Space Flight Center (GSFC), there are several ongoing related activities that taken together, act as pathfinders to future self-managing sensor constellations. Similar to commuters autonomously optimizing their route, future constellation components, whether they are orbital satellites, unmanned systems, or ground components will autonomously optimize their operations activities. These systems will act independently while accomplishing coordinated observations that saitsfy complex scientific objectives. Taken together, these smart components will enable more cost-effective management of future satellite constellations and other sensor platforms.

The pathfinder activities implement a model-based operations approach integrating groups of autonomous sensor nodes to collaborate for observations. Autonomous event detections made by a source node are broadcast through the sensor web communications fabric in real time to trigger follow-up observation requests by other sensors. Middleware to enable interoperability between ground and space-based components provides a plug and play environment for new software and algorithms.

The sensor web technology activities use the Earth Observing 1 (EO-1) satellite [1] as an on-orbit testbed. EO-1 was launched November 21, 2000 as part of the New Millenium Program at NASA and was originally designed as a one-year mission to validate revolutionary new space technologies. It hosts three land remote sensing instruments - the Advanced Land Imager, the Hyperion hyperspectral imager, and the Atmospheric Corrector - in addition to a dozen new, ground-breaking spacecraft technologies. After its prime mission, it was converted into an orbital demonstration platform, and in particular, used to validate a number of sensor web concepts. Figure 1 depicts the EO-1 satellite.

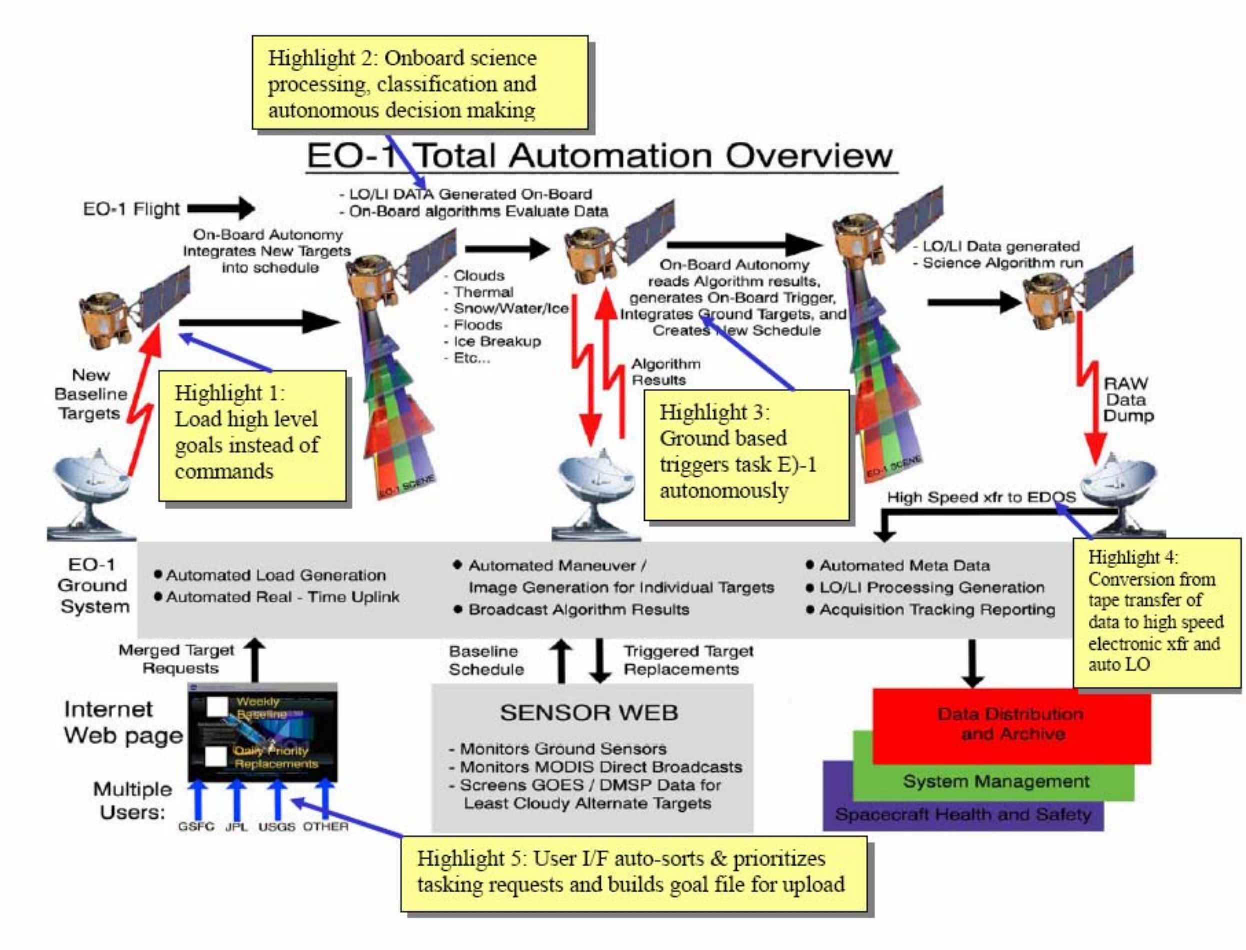

Figure 2 Overview of autonomy and automation software installed on the EO-1 mission

Figure 2 depicts a high level overview of key automation and autonomy capabilities integrated into the EO-1 mission. The highlights are as follows:

(1) Tasking of the EO-1 satellite with high level goals instead of specific commands

(2) Onboard science processing, classification and autonomous decision-making

(3) Autonomous triggers to task EO-1 from both the ground and other space-based assets

(4) User interface to automatically sort and prioritize tasking requests. This includes building the goal files and automatically uploading them to EO-1.

These capabilities continue to evolve and become more robust as the sensor web vision and architecture crystallizes.

2 Tasking EO-1 Using High Level Goals

One of the key upgrades to the operations concept for EO-1 was to work with high-level goals instead of a series of individual lower level commands and command loads [3][4]. This level of abstraction enables the user to be isolated from much of the underlying detail required to task the EO-1 satellite. When the original process of tasking EO-1 was defined, approximately 60 steps were required to task EO-1 for one image. When the autonomy and automation software was created, all of these steps were encapsulated in high-level goal processing software that handles the underlying detail.

The ground software used is either Automated Scheduling and Planning Environment (ASPEN)[9], a NASA Jet Propulsion Laboratory (JPL) application or Science Goal Monitor (SGM) [3], a GSFC application. The EO-1 spacecraft also ingests high level goals via Continuous Activity Scheduling Planning Execution and Replanning (CASPER) software [4]. The CASPER software is an eight megabyte executable that is uploaded into RAM onboard one of EO-1's flight processors and, once invoked, intreprets the high level goals onboard, manages the onboard details of acquiring an image and processing the data, and manages onboard replanning of the short term integrated schedule of activities. We used the SGM as a pathfinder towards working with high level goals and then evolved towards using the ASPEN/CASPER combination in general.

3 Onboard Science Processing, Classification and Autonomous Decision Making

The centerpiece of our improved operations is the autonomy that was installed onboard EO-1, the Autonomous Sciencecraft Experiment (ASE) [9]. ASE is comprised of CASPER and additional algorithms that can perform the following functions:

(1) Level 0 and level 1 processing onboard

(2) Classification of images to screen for clouds [5], thermal anomalies, floods, change detection, generalized feature detection [6].

(3) Select alternate targets from the original plan by replacing high-level goals in the onboard goal file. The replacements can either be triggered onboard by one of the classifiers or can be loaded from the ground as a result of an autonomous trigger from an installed instrument suite.

4 Autonomous triggers to task EO-1

In the beginning of the mission, all tasking of EO-1 to perform imaging with its three instruments was meticulously planned by a team of scientists, engineers and operations personnel on a daily basis. Over the last two years, the operations concept has evolved to the point that autonomous triggers can task EO-1 without human intervention on a full time basis. In our sensor web experiments, transient events such as volcano eruptions trigger EO-1 images via ASPEN or SGM. These triggers are folded into the normal tasking plan via a priority scheme which enables higher priority tasking requests to automatically replace lower priority tasking requests in the onboard schedule. Because we are working with high level goals, this process is greatly simplified since we are dealing with a higher level of abstraction than in the beginning of the mission.

Figure 3 depicts at a high level, various sensor web experiments that have been conducted. Note the variety of software tools used the the variety of applications. Autonomous triggers included other satellites such as Terra, Aqua and GOES; and ground instruments such as the tilt meter to detect volcanic activity at Kilauea.

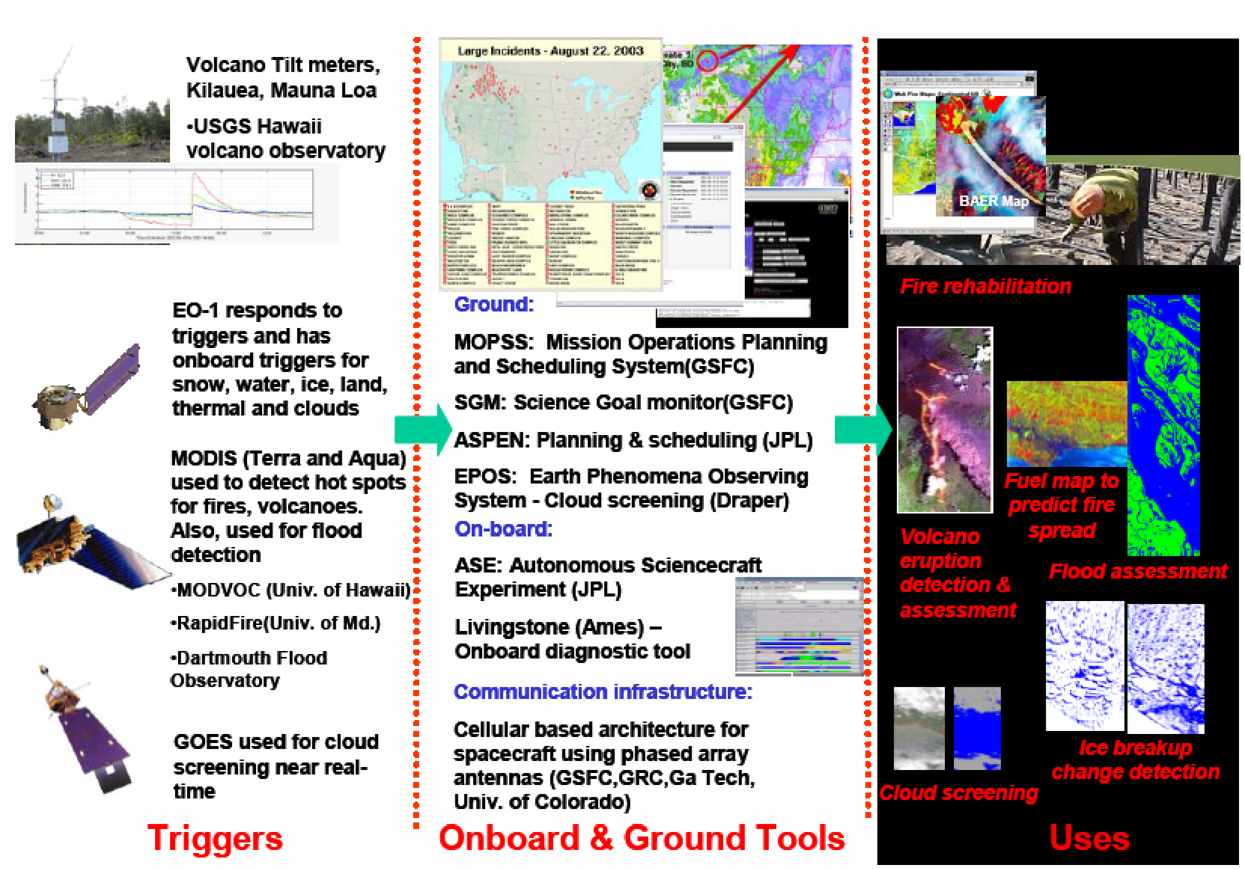

Figure 3 Overview of the various triggering combinations along with some of the applications that were used with EO-1.

5 User Interface to Automatically Sort and Prioritize Tasking Requests

A web interface has been prototyped that provides a mechanism to input tasking requests. Up to now, we have used the customer interface at the United States Geological Survey (USGS) Center for Earth Resource Observations and Science (EROS). This required weekly meetings with the

EROS representative, the Flight Operations Team lead, the EO-1 Mission Systems Engineer, and the EO-1 Deputy Scientist to integrate the various customer requests. However, on the new system, all of the priority schemes have been encoded in software, so the weekly meeings will no longer exist other than for special exceptions. The translation of tasking requests to uplinkable goal files as well as the uplink and ingest onboard are all automated.

6 Communications Fabric

It should be noted that key to making sensor webs work is the communications fabric that exists between the various software applications. Inter-process communications is readily available for ground-to-ground based software processes. However, sensor webs require communications between software applications that are resident onboard satellites and the ground. Therefore, for our experiments we devised a software bus onboard EO-1 in which any application can address any other application and easily send a message as a means to coordinate activities. We extended this concept by using internet technology interfaces to create a virtual connection between satellites, for example, using the Terra satellite as a triggering source and the EO-1 satellite. Also, we used an internet site to create a virtual connection between ground instruments, such as tilt meters installed on the Kilauea volcano, EO-1's planning software, and the EO-1 satellite. But to really make sensor webs work, an internet-like connection is needed to create a very responsive system.

7 Lessons Learned and Future Implications

By treating every component in a constellation as a software component over a network, we can create a collaborative environment that enables sensor webs. The key to the successes on EO-1 resided in the fact that EO-1 was built with an extra onboard computer and extra memory which is modifiable on-orbit. Future missions should be built with extra hardware resources to enable new software applications to be installed on-orbit and thus add new capability for a mission.

Experimental results in mission autonomy allowed us to explore the constraints related to conflict resolution for competing triggering requests. In addition, the implementation of fully automated systems uncovered error conditions that were a result of interaction with pre-existing operations procedures. As these problems were identified, additional intelligence was added to queuing scripts and ingest routines to eliminate these glitches. Many of these lessons were learned during on-orbit debugging of new code installations, since many of the functions could not be fully checked on the ground due to limitations in flight software simulators.

Figure 4 represents a future vision in which sotware can be loaded onto satellites in a "plug and play" manner and then made to run without the present hassle of extensive testing. Efforts such as these and other related activities are going to enable increased flexibility and thus cost-effective sensor webs.

As an indirect result of the experiments conducted on EO-1, which added various autonomy and automation software components on both the ground and onboard the satellite, the cost of EO-1 operations has dropped dramatically. It is expected that the actual cost of operations will drop further in our totally automated mode in Fiscal Year (FY) 2006 which begins October 1, 2005. Figure 5 depicts the monthly cost of operating the EO-1 mission, where the solid line depicts the actual costs and the dashed line depicts the projected monthly cost as new software components are installed into operations.

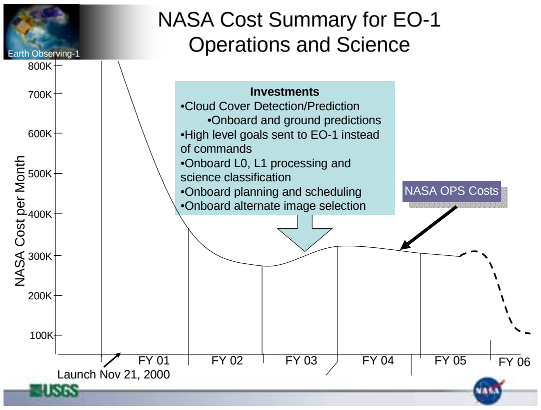

Figure 5 Cost profile of EO-1 with key software components identi

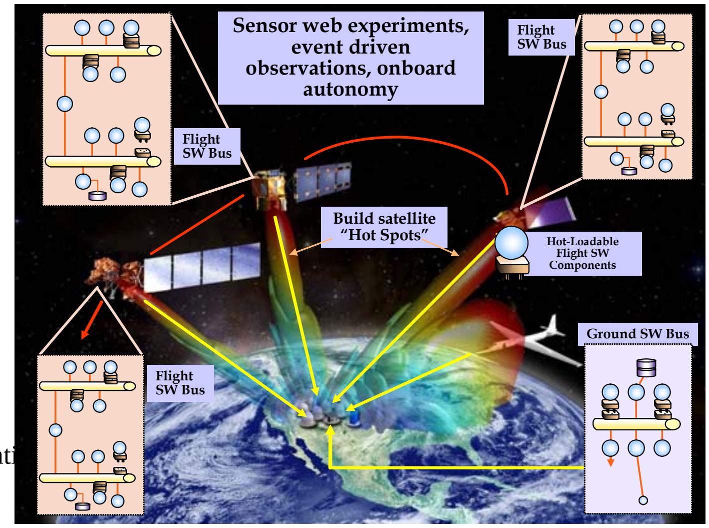

Figure 4 Sensor Web vision with seamless communications beteween space and ground software elements

8 Conclusion

Surprisingly, we discovered that when we connected various software components to experiment with sensor webs, we not only were able to validate some future operations concepts, but were also able to acquire immediate benefits via lowering the cost of EO-1 operations and enabling additional science. We were able to go further than anticipated which leads us to believe that sensor webs can be put into place sooner than expected to provide some useful science return. In fact, this was what was demonstrated on EO-1.

9 References

[1]Goddard Space Flight Center, EO-1 Mission page: URL: http://EO-1.gsfc.nasa.gov [cited 10 May 2005].

[2]Ingram, M.A.; Romanofsky, R.; Lee, R.; Miranda., F.; Popovic, Z.; Langley, J.; Barott, W.; Ahmed, M.; Mandl, D.; “Optimizing Satellite Communications with Adaptive and Phased Array Antenna” ESTC 2004, Palo Alto, CA., June 2004

[3]Koratkar, A; Grosvenor, S.; Jung, J.; Hess, M.; Jones, J.; “Autonomous Multi-sensor Coordination: The Science Goal Monitor”, SPIE 2004 Remote Sensing of the Atmosphere, Ocean, Environment, and Space; Honolulu, Hawaii, Novemebr 2004

[4]Sherwood, R., Chien, S., Davies, A., Mandl, D., Fryes, S., “Realtime Decision Making on EO-1 Using Onboard Science Analysis” SPIE 2004 Remote Sensing of the Atmosphere, Ocean, Environment, and Space; Honolulu, Hawaii, November 2004

[5]Griffin, M., Burke, H., Mandl, D., and Miller, J., “Cloud Cover Detection Algorithm for the EO-1 Hyperion Imagery,” Proceedings of the 17th SPIE AeroSense 2003, Orlando, FL, April 2003.

[6]Burl, M. C., et al. “Automated Detection of Craters and Other Geological Features,” Proceedings of the International Symposium on Artificial Intelligence Robotics & Automation in Space, Montreal, Canada, June 2001.

[7]Mandl, D., et al, “Linking Satellites Via Earth “Hot Spots” and the Internet to Form Ad Hoc Constellations”, SPIE 2004 Remote Sensing of the Atmosphere, Ocean, Environment, and Space; Honolulu, Hawaii, November 2004

[8]Mandl, D.; “Experimenting with Sensor Webs Using Earth Observing 1”, IEEE Aerospace Conference, Big Sky, MT, March 2004

[9]Mandl, D.; Grosvenor, S; Frye, S; Sherwood, R; Davies, A; Chien, S.;Cichy, B.; et al, “Sensor Webs; Autonomous Rapid Response To Monitor Transient Science Events” AMS 2005 Conference, San Diego, CA, January 2005