Experimenting with an Evolving Ground/Space-based Software Architecture to Enable Sensor Webs

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Abstract – A series of ongoing experiments are being conducted at the NASA Goddard Space Flight Center to explore integrated ground and space-based software architectures enabling sensor webs. A sensor web, as defined by Steve Talabac at NASA Goddard Space Flight Center(GSFC), 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 resource, such as communication channels and ground station,s while automatically coordinating their activities.

There have been five ongoing activities which include an effort to standardize a set of middleware. This paper will describe one set of activities using the Earth Observing 1 satellite, which used a variety of ground and flight software along with other satellites and ground sensors to prototype a sensor web. This activity allowed us to explore where the difficulties 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.

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1 Introduction

At NASA/Goddard Space Flight Center (GSFC), there are five ongoing related activities that together, act as pathfinders to future self-managing constellations. Similar to commuters autonomously optimizing their route, future constellation components, whether they are satellites, satellite subsystems or ground components will autonomously optimize their operations activities. Taken together, these smart components will enable more cost-effective management of complex future constellations.

The specific activities are:

(1) Earth Observing 1 sensor web experiments

(2) Space Technology 5 model-based operations approach

(3) Adaptive sensor fleet – a group of autonomous water-crafts that collaborate for observations

(4) Aqua triggered Aura image targeting – real time cloud detection by the Aqua satellite triggers the Aura satellite, which is following Aqua, to point its TESS instrument into cloud free areas

(5) Goddard Mission Services Evolution Center (GMSEC) – middleware to enable interoperability between ground components. For more info see: https://gmsec.gsfc.nasa.gov

This paper will discuss activity (1) from the list above.

The Earth Observing 1 (EO-1) satellite[1], launched November 21, 2000, is part of the New Millenium Program at NASA and was originally designed as a one-year mission to validate revolutionary space technologies. It hosts three instruments. After its prime mission, it was converted into an orbital testbed, and in particular, used to validate a number of sensor web concepts. Figure 1 depicts the EO-1 satellite.

Figure 1 The Earth Observing 1 satellite

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. Projected cost of operations will drop further in our totally automated mode in Fiscal Year (FY) 2006 which begins October 1, 2005. Figure 2 depicts the monthly cost of operating the EO-1 mission, where the solid line depicts the actual costs thus far and the dashed line depicts the projected monthly cost when the final software components are installed into operations.

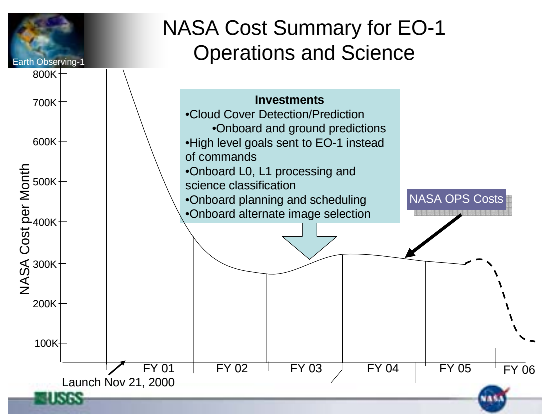

Figure 2 Cost profile of EO-1 with key software components identified on the inset box

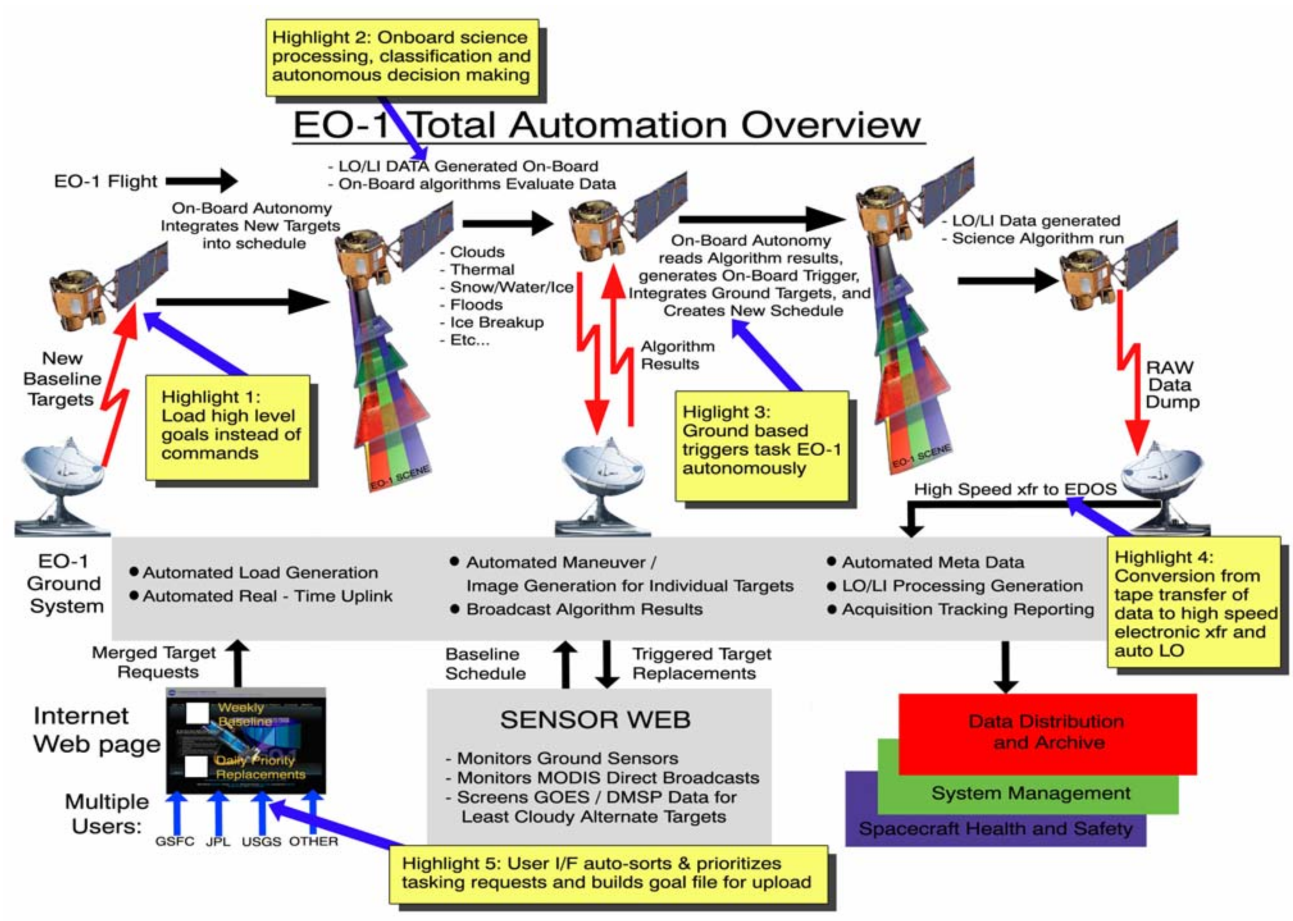

Figure 3 Overview of autonomy and automation software installed on the EO-1 mission

Figure 3 depicts a high level overview of key automation and autonomy capabilities integrated into the 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) High speed electronic transfer of science data versus tape transfer from the ground stations

(5) User interface to automatically sort and prioritize tasking requests. This includes building the goal files for upload to EO-1.

The rest of the paper describes each of these areas and how these capabilities together act as a pathfinder towards a sensor web vision.

2 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 enabled the user to be isolated from much of the underlying detail required to task the EO-1 satellite. In fact, when the original process of tasking EO-1 was defined, there was something in the order of 60 steps 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, which in turn handles the underlying detail. The ground software we are using is either Automated Scheduling and Planning Environment (ASPEN)[9], or Science Goal Monitor (SGM) [3]. The EO-1 spacecraft also ingests high level goals via Continuous Activity Scheduling Planning Execution and Replanning (CASPER) software [4] which in turn manages the onboard details of acquiring an image and managing the short term integrated schedule of images. We used the SGM as a path finder 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, Autonmous 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

(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 ground trigger such as a ground instrument.

4 Autonomous triggers to task EO-1

Whereas in the beginning of the mission, all tasking of EO-1 to perform imaging with one of its three instruments were meticulously planned by a team of scientists, engineers and operations personnel on a daily basis, we have evolved the operations concepts to the point that autonomous triggers can task EO-1. In our sensor web experiments, transient events such as volcanoes trigger EO-1 images via ASPEN and SGM. These triggers are folded in to the normal tasking plan via a priority scheme which enables higher priority tasking requests to automatically replace lower priority tasking requests. 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 4 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.

5 High Speed Electronic Transfer

Presently, science data is mailed from the polar ground stations via expensive AMPEX tapes. We are planning to transition to the use of T3 lines to electronically transfer the large amounts of science data from those sites. Previously, the capacity of the existing lines was insufficient to handle the data volume. Thus, we will be able to remove one more manual step in the process.

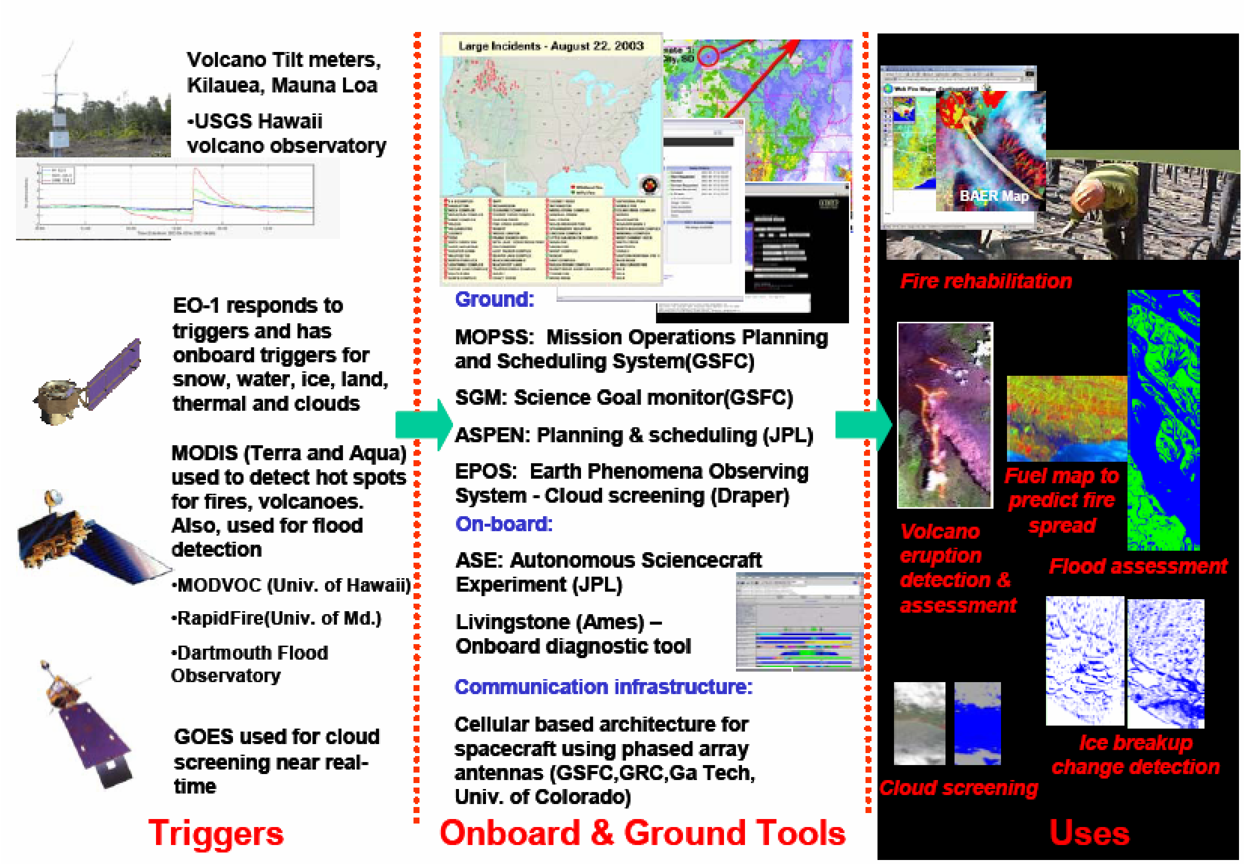

Figure 4 Overview of the various triggering combinations along with some of the applications that were used with EO-1.

6 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 Observation and Science (EROS) . This required weekly meetings with the EROS representative, the FOT lead, the EO-1 Mission Systems Engineer and the EO-1 Deputy Scientist to integrate the various customer requests according to an agreed upon priority scheme. 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.

7 Communications Fabric

It should be noted that key to making sensor webs work, is the communications fabric that exists between the various software applications. Solutions are readily available for ground-based software, however for sensor webs, these solutions have to be extended to make ground and flight software seamlessly interoperable. 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 web interfaces to create a virtual connection between satellites, for example, between the Terra satellite, used as a triggering source and the EO-1 satellite. Also, we used a website to create a virtual connection between a ground based tilt meter 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.

8 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 Mongoose onboard computer and extra memory which 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.

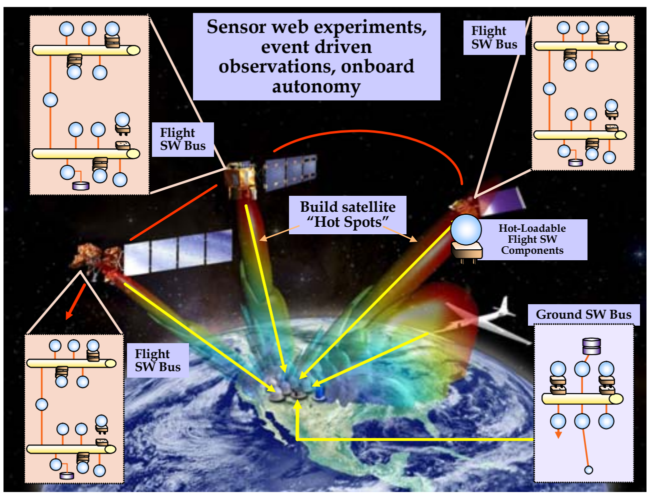

Figure 5 Sensor web vision with seamless communications between space SW and ground SW

Figure 5 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 required now. Efforts such as those depicted in [2], [7] and the GMSEC effort mentioned earlier are going to enable this increased flexibility and thus enable cost-effective sensor webs.

9 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, that is what we demonstrated on our current mission, EO-1.

10 References

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