Earth Observing 1: A Pathfinder to Future Sensor Webs

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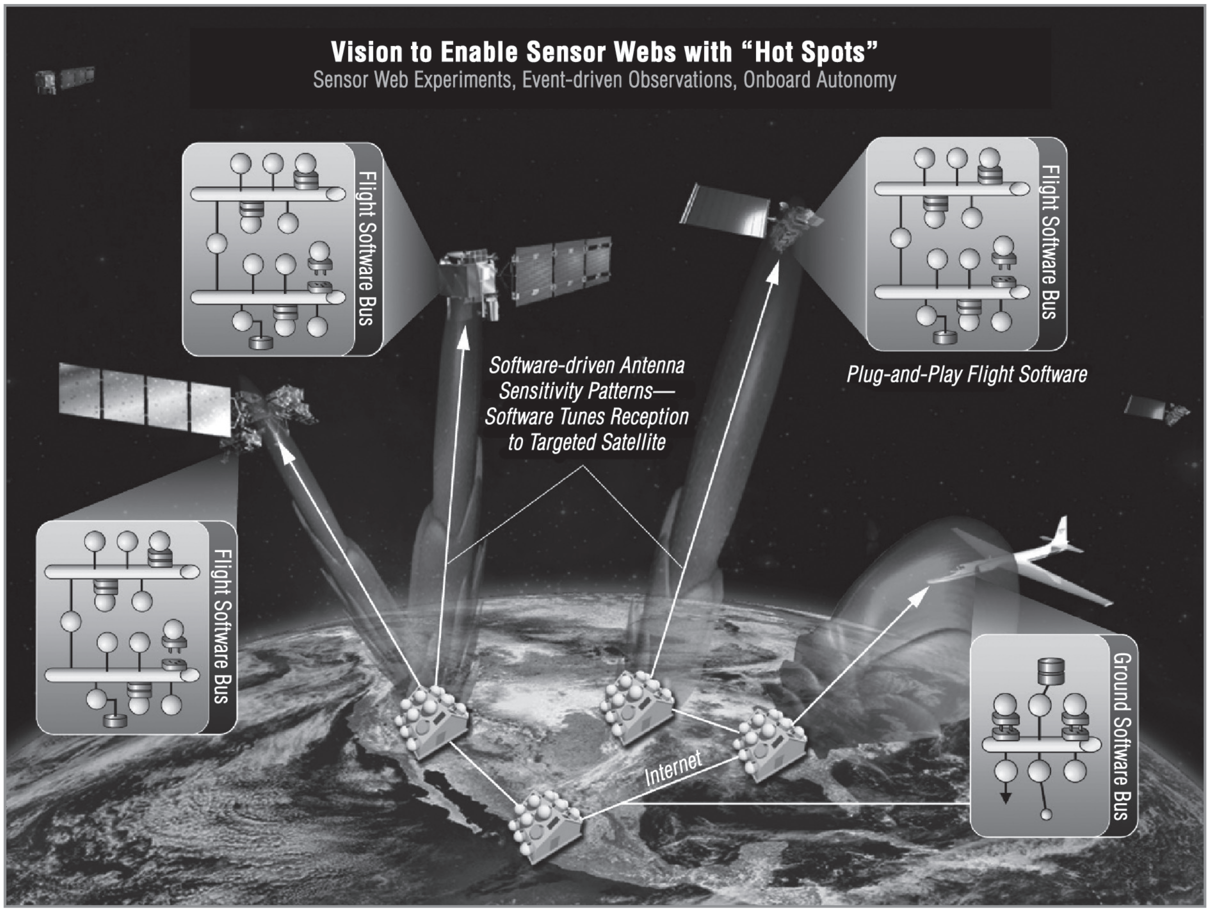
Overview

The Earth Observing 1 (EO-1) satellite was launched on November 21, 2001 as a one-year technology validation mission under the NASA New Millennium Program. The EO-1 mission is managed and operated by the Goddard Space Flight Center (GSFC). After a flawless and successful first year of operations, in which all of the onboard technologies were validated, the mission was extended and reformulated to utilize the three onboard imagers for continued science research into hyperspectral imaging, and to be a pathfinder for new sensor web operations concepts. **Figure 1** depicts the vision used in designing the EO-1 sensor web experiments, which includes integration of sets of heterogeneous sensors to collaborate autonomously triggered by real-world events. Middleware, software radio and *plug and play* software environments for both the ground and flight software further facilitate this vision (a software radio is a radio that uses software to define channel waveform modulations).

Since the end of the first year of operation, EO-1 has been flying in an on-orbit testbed mode and will continue operating in this mode for at least another two years, barring onboard component failure. During this extended-mission phase, EO-1 has been re-outfitted with new flight software in order to take steps towards the vision depicted in **Figure 1**. Specifically, we installed new software onboard EO-1 to: 1) perform onboard Level 0 and Level 1 data processing; 2) perform onboard pixel classification to detect features such as clouds, thermal events, water, and ice; 3) enable autonomous onboard decision-making based on triggers from the classification software; and 4) autonomously schedule and task EO-1 imaging events. These capabilities were linked to other satellites and ground instruments to form various *ad hoc* sensor webs enabling various operations concepts that would be useful for future NASA missions. The sensor web and autonomy capabilities developed thus far have been retained and used operationally on EO-1 and have served

Figure 1: Vision for future sensor webs using inter-sensor connectivity via software radio antennas and *plug-and-play* ground and flight software.



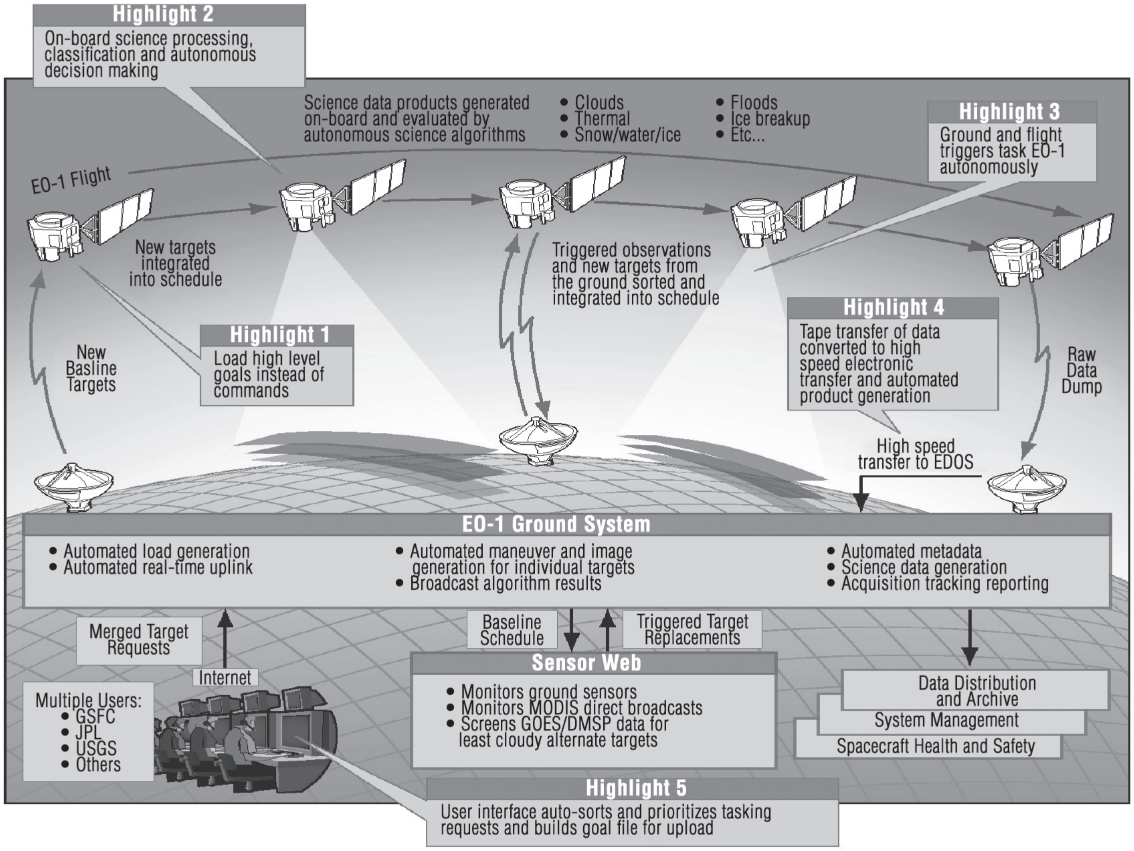


Figure 2: Overview of autonomy and automation software installed on EO-1 to date.

to reduce the cost of operations by over 50%. **Figure 2** shows a summary of the software installed on EO-1 for this experiment.

Sensor Web Definition

A *sensor web* is a coherent collection of space-based and/or ground-based sensors and computation nodes linked by a communication fabric that collectively act as a single, dynamically adaptive, observing system. An example sensor web might be one satellite observing a target event and triggering another satellite autonomously. Another example might be a ground instrument triggering a satellite image. A more unusual twist might be a modeling software package requiring a key observation in real-time to make a prediction and thus autonomously triggering a desired satellite image.

EO-1 Background

The EO-1 mission was originally designed to be a one-year mission to validate revolutionary space technologies. It hosts three land remote sensing instruments: the Advanced Land Imager (ALI), a multispectral imager, and Hyperion and an Atmospheric Corrector, both hyperspectral imagers. Furthermore, it hosted eight new spacecraft technologies. **Figure 3** depicts the EO-1 satellite.

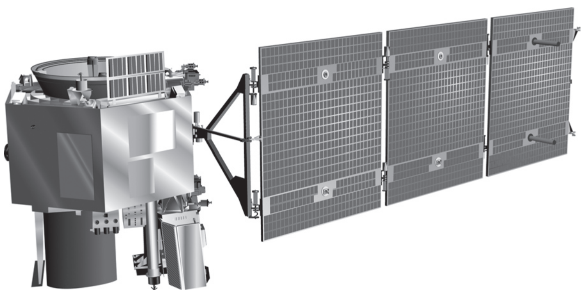
Key Features of EO-1 Autonomy and Automation:

The highlights are as follows:

- tasking of the EO-1 satellite with high-level goals instead of specific commands;
- onboard science processing, classification, and autonomous decision-making;
- ability to accept autonomous triggers from both space- and ground-based assets; and
- automated user interface to sort, prioritize, and build tasking files for EO-1

The Jet Propulsion Laboratory (JPL) led the autonomy software development in collaboration with Goddard and it was called the Autonomous Science Experi-

Figure 3: The EO-1 Satellite



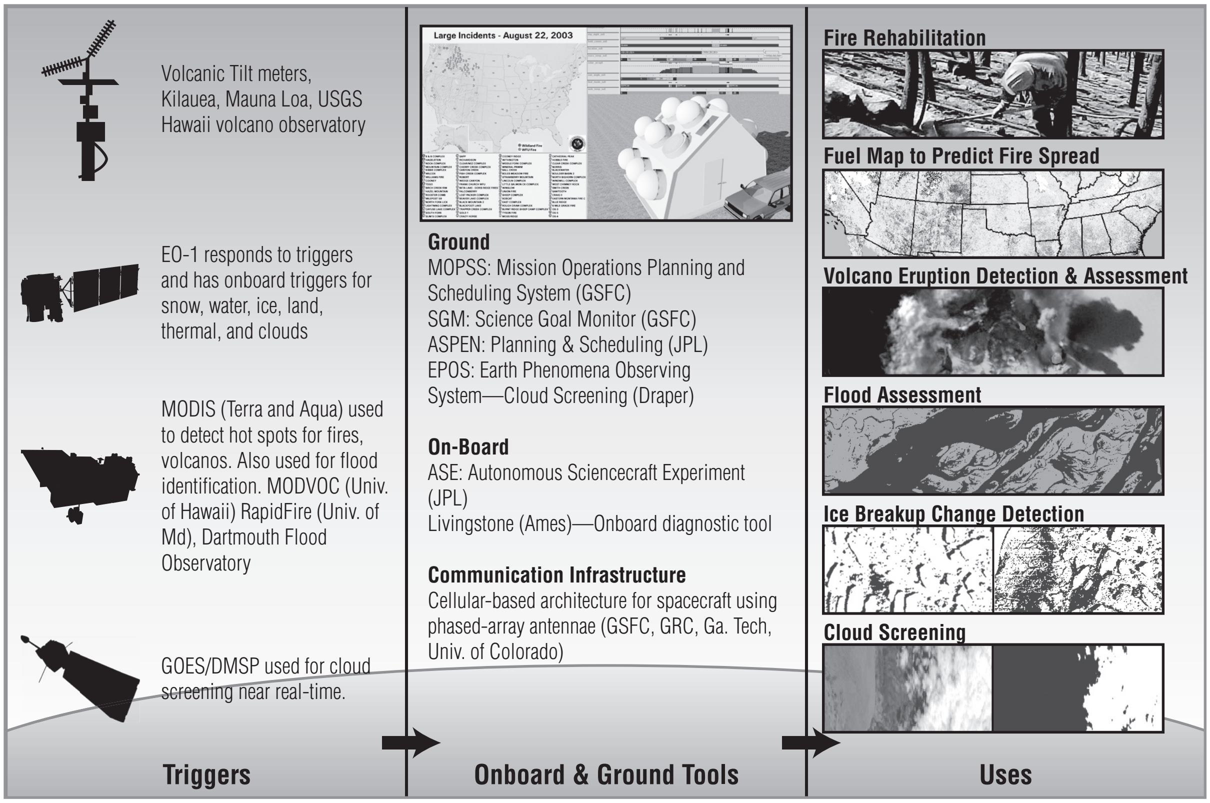


Figure 4: Overview of various EO-1 sensor web experiments conducted.

ment (ASE). ASE is composed of three components, Continuous Activity Scheduling and Planning, Execution and Replanning (CASPER), which is an onboard planner and scheduler, Spacecraft Command Language (SCL), which acts as a middleware execution engine and finally the science processing software to perform Level 0, Level 1 and additional science classification and processing. There is also a complementary ground piece of software called Automated Scheduling and Planning Environment (ASPEN), which works collaboratively with CASPER to process triggers and imaging requests for use by CASPER. In particular, triggers and requests are automatically sorted and prioritized and then converted into a list of high-level goals that can be worked on by CASPER. Prior to the development of ASPEN, we used Science Goal Monitor (SGM) which was software developed at Goddard, to act as a pathfinder for this functionality. The ASE software won the NASA 2005 Software of the Year Award.

Experiments with EO-1

A variety of experiments were conducted with EO-1 using the autonomy and automation that was integrated. **Figure 4** depicts the variety of scenarios that were exercised. Note that a variety of triggers were received from the Terra and Aqua spacecraft to detect thermal activity, such as volcanoes and wildfires, and subsequently triggers were sent to the Geostationary Operational Environmental Satellite (GOES) and the Defense Meteorological Satellite Program (DMSP) to detect clouds and perform cloud screening. A tiltmeter in Kilueha, Hawaii which triggers an EO-1 image whenever the ground moves as a result of a volcano. The experiments with Terra and Aqua involved using the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument to detect hot spots and have EO-1 automatically take a high-resolution image of the area. Meanwhile we were able to use other satellite data to perform real-time cloud screening to allow EO-1 to autonomously choose the least cloudy of conflicting image choices that were available. Thus we were able to demonstrate increased efficiency for utilization of EO-1 by demonstrating reduction of lag time from event detection to imaging and reduction of cloud-obscured imagery.

Other experiments included setting up a demonstration communication link to EO-1 via experimental software radio antennas, the future target being the transformation of ground antennas to act more like wireless routers for satellites with no moving parts. Also, during the Fall of 2005, we collaborated with a University of Maryland at Baltimore County (UMBC) sensor network class in which the students built projects which linked a sensor network, a mini-rover, and EO-1 (**Figure 5**). Demonstrations were held at UMBC and at Goddard and were attended by UMBC faculty, Goddard personnel and a *Baltimore Sun* reporter. In one of the class experiments, one of six ground sensor *motes*

Figure 6: Mini-rover in action during one of the demonstrations (insets). UMBC Sensor Network class taught by Dr. Younis (main picture).

was turned off to simulate failure, which then autonomously directed the mini-rover to find the broken mote and then to take a picture of the area. Furthermore, a message was sent to a website that autonomously tasked EO-1 to image the UMBC campus. **Figure 6** depicts experiment day in an atrium at UMBC.

Future Efforts

The sensor web experiments conducted thus far with EO-1 have acted as a springboard to more-complex future experiments. In particular, we will address interoperability issues by making use of emerging standards. In particular, we will be using Goddard Mission Services Evolution Center (GMSEC) 6, Core Flight Executive (CFS)6 and Sensor Modeling Language (SensorML). GMSEC together with CFS, both efforts managed at GSFC, to provide a ground and flight message bus. SensorML is a widely accepted interoperability standard for sensors sponsored by the Open Geospatial Consortium (OGC). We have begun to use the Cosmic Hot Interstellar Plasma Spectrometer (CHIPS) satellite together with these standards in similar experiments to extend the sensor web experiments. CHIPS features a ground-to-space Internet Protocol (IP) interface along with a more-advanced onboard CPU, and thus is better suited to perform these type of experiments. Thus we will be able to more closely replicate the vision outlined in **Figure 1**.

References

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3. Information on ASE, CASPER and ASPEN: *ase.jpl.nasa.gov*

4. 45 papers and 41 more articles on EO-1 sensor web work at: *eo1.gsfc.nasa.gov/new/general/resources/papers.html*

5. Information on EO-1 in general: *eo1.gsfc.nasa.gov*

6. Information on GMSEC and CFS: *gmsec.gsfc.nasa.gov* ▬