

Sensor Webs for Science: New Directions for the Future

Rob Sherwood^{*} and Steve Chien[†]

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA, 91109, USA

Sensor webs for science have evolved considerably over the past few years. New breakthroughs in onboard autonomy software have paved the way for space-based sensor webs. For example, an autonomous science agent has been flying onboard the Earth Observing One (EO-1) Spacecraft for several years. This software enables the spacecraft to autonomously detect and respond to science events occurring on the Earth. The package includes software systems that perform science data analysis, deliberative planning, and run-time robust execution of the generated plans. This software has demonstrated the potential for space missions to use onboard decision-making to detect, analyze, and respond to science events, and to downlink only the most valuable science data. This paper will briefly summarize this experiment as well as describe how the software has been used in conjunction with other satellites and ground sensors to form an autonomous sensor-web. In addition to these applications, which represent the current state of the art for autonomous science and sensor webs, we will describe the future research and technology directions in both Earth and Space Science. Several technologies for improved autonomous science and sensor webs are being developed at NASA. This paper will present an overview of these technologies. Each of these technologies advances the state of the art in sensorwebs in different areas, allowing for increased science within the domain of interest. Demonstration of these sensorweb capabilities will enable fast responding science campaigns of both spaceborne and ground assets.

Nomenclature

ALI	= Advanced Land Imager
ASE	= Autonomous Sciencecraft Experiment
CASPER	= Continuous Activity Scheduling Planning Execution and Replanning software
EO-1	= Earth Observing One
SCL	= Spacecraft Command Language

I. Introduction

SINCE January 2004, the Autonomous Sciencecraft Experiment (ASE) running on the EO-1 spacecraft has demonstrated several integrated autonomy technologies to enable autonomous science. Several science algorithms including: onboard event detection, feature detection, and change detection are being used to analyze science data. These algorithms are used to downlink science data only on change, and detect features of scientific interest such as volcanic eruptions, growth and retreat of ice caps, flooding events, and cloud detection. These onboard science algorithms are inputs to onboard planning software that can modify the spacecraft observation plan to capture science events of high value. This new observation plan is then 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.

The ASE onboard flight software includes several autonomous software components:

- Onboard science algorithms that 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

^{*} Program Manager, Earth Science Information Systems, M/S 180-401.

[†] Principal Investigator, Autonomous Sciencecraft Experiment, M/S 126-347.

- Robust execution management software using the Spacecraft Command Language (SCL)¹ package to enable event-driven processing and low-level autonomy
- The Continuous Activity Scheduling Planning Execution and Replanning (CASPER)² software that replans activities, including downlink, based on science observations in the previous orbit cycles

The onboard science algorithms analyze the images to extract static features and detect changes relative to previous observations. The software uses EO-1 Hyperion instrument images 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, ice melt, and lava flows). Using these algorithms onboard enables retargeting and search, e.g., retargeting the instrument on a subsequent orbit cycle to identify and capture the full extent of a flood.

Although the ASE software is running on the Earth observing spacecraft EO-1, it will also be used on other interplanetary space missions. On these missions, onboard science analysis will enable capture of short-lived science phenomena. In addition, onboard science analysis will enable data to be captured at the finest time-scales without overwhelming onboard memory or downlink capacities by varying the data collection rate on the fly. The software is currently undergoing infusion on the Mars Exploration Rovers Mission and Mars Odyssey Mission. Examples of possible future mission applications of this software include studying: 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) generates mission operations plans from goals provided by the onboard science analysis module. The model-based planning algorithms enable rapid response to a wide range of operational scenarios based on a model of spacecraft constraints, including faster recovery from spacecraft anomalies. The onboard planner accepts as inputs the science and engineering goals and ensures high-level goal-oriented behavior.

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.

II. The EO-1 Mission

Earth Observing-1 (EO-1) is the first satellite in NASA's New Millennium Program Earth Observing series³. The goal of the EO-1 primary mission was 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 between 5 (at the equator to 45 degrees) and 16 (at the poles) over-flights of any particular area per 16-day cycle. For each scene, between 13 to as much as 48 Gbits of data from the Advanced Land Imager (ALI), Hyperion, and Atmospheric Corrector (AC) are collected and stored on the onboard solid-state data recorder.

EO-1 is currently in extended mission, having surpassed its original technology validation goals. As an example, over 35,000 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. The Hyperion is a high-resolution imager capable of resolving 220 spectral bands (from 0.4 to 2.5 μm) with a 30-meter spatial resolution. The instrument images a 7.7 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. The first M5 is used for the EO-1 command and data handling functions. The other M5 is 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 ASE software operates on the WARP M5. This provides an added level of safety for the spacecraft since the ASE software does not run on the main spacecraft processor.

III. Onboard Science Analysis

The first step in the autonomous science decision cycle is detection of interesting science events. Twelve of the Hyperion spectral bands are used to classify the pixels within each image as land, ice, water, snow, clouds, and fresh lava. Using the pixel classification, a number of science analysis algorithms are being used including:

- Thermal anomaly detection – uses infrared spectra peaks to detect lava flows and other volcanic activity. (See Figure 1.)

- Cloud detection⁴ – uses intensities at six different spectra and thresholds to identify likely clouds in scenes. (See Figure 2.)
- Flood scene classification – uses ratios at several spectra to identify signatures of water inundation as well as vegetation changes caused by flooding. (See Figure 3.)
- Change detection – uses 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 Figure 3.)

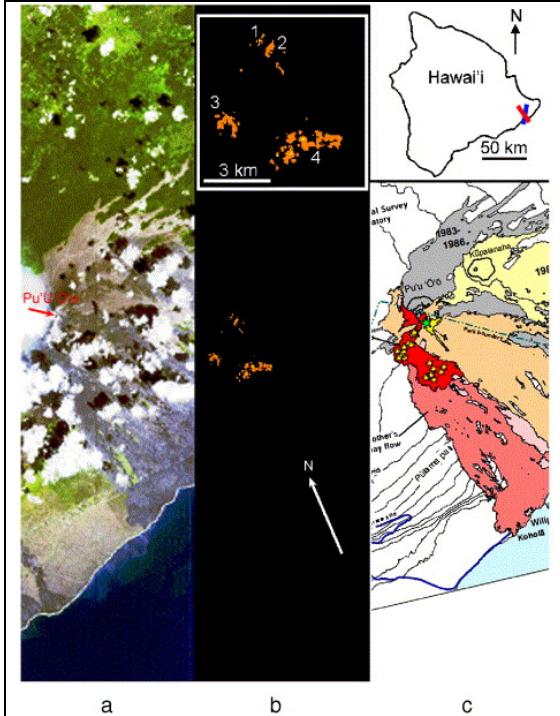


Figure 1. Kilauea Volcano. (a) the visible image of Kilauea, Hawaii on 24 January 2004; (b) Thermal Classifier output including an inset enlargement of the active area; (c) shows the USGS – Hawaiian Volcano Observatory map showing volcanically active areas in January 2004. In (c), yellow areas delineate the Martin Luther King (MLK) flows in January 2004.

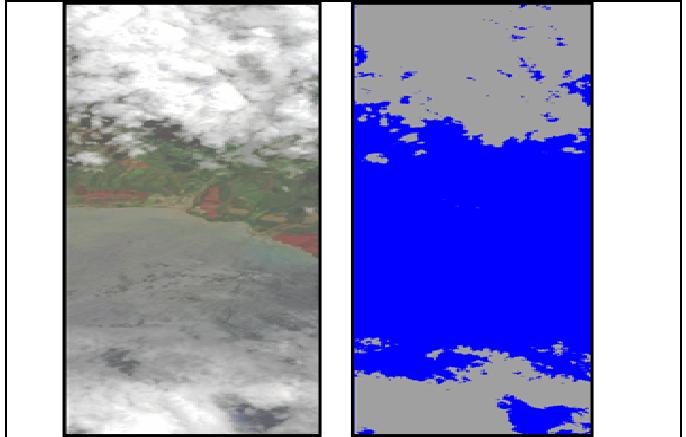


Figure 2. Cloud Detection – visual image at left, grey in right image indicates detected cloud.

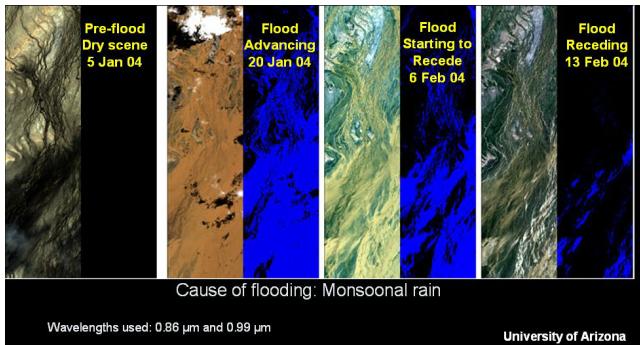


Figure 3. Flood detection time series imagery of Australia's Diamantina River with visual spectra at left and flood detection map at right.

Figure 1 contains both the visible image and thermal detection at the Kilauea volcano in Hawaii. The infrared bands are used to detect hot areas that might represent fresh lava flows within the image. In the second third of this image, these hot spots are shown in yellow and orange. The area of hot pixels can be compared with the count of hot pixels from a previous image of the same area to determine if change has occurred. If there has been any change, a new image might be triggered to get a more detailed look at the eruption.

Figure 2 shows a Hyperion scene and the results of the cloud detection algorithm⁴. This MIT Lincoln Lab developed algorithm is able to discriminate between cloud pixels and land pixels within an image. Specifically, the grey area is clouds while the blue area is land. The results of this algorithm can be used to discard images that are too cloudy by setting a cloud threshold over which the image should be deleted. Images with low cloud cover can be further analyzed for science value.

Figure 3 contains four EO-1 Hyperion images of the Diamantina River in Australia, along with their corresponding classification images to the right of each image. The first image is a baseline image of the river in a dry state. The second image taken two weeks later shows a large flood area with blue representing water pixels. The final two images show the

flood receding over time. The results of the algorithm are compared with land and water counts from a previous image to determine if flooding has occurred. If significant flooding has been detected, the image can be downlinked. In addition, a new goal can be sent to the CASPER planning software to image adjacent regions on subsequent orbits to determine the extent of the flooding.

The JPL developed thermal anomaly algorithm uses the infrared spectral bands to detect sites of active volcanism. There are two different algorithms, one for daytime images and one for nighttime images. The algorithms compare the number of thermally active pixels within the image with the count from a previous image to determine if new volcanism is present. If no new volcanism is present, the image can be discarded onboard. Otherwise, the entire image or the interesting section of the image can be downlinked.

Arizona State University's Snow-Water-Ice-Land (SWIL) algorithm is used to detect lake freeze/thaw cycles and seasonal sea ice. The SWIL algorithm uses six spectral bands for analysis.

IV. 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 relevant spacecraft and mission constraints. The Continuous Activity Scheduling Planning Execution and Replanning (CASPER)² 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 approach⁵ 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. In the case of EO-1, the Mongoose V CPU has approximately 8 MIPS. Of the 3 software packages, CASPER is by far the most computationally intensive. For that reason, our optimization efforts were focused on CASPER. In light of the performance constraints, we developed an EO-1 CASPER model that didn't require many planning iterations. For that reason, the model has only a handful of resources to schedule. This ensures that CASPER is able to build a plan in tens of minutes on the relatively slow CPU.

CASPER is responsible for 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. This event may warrant a high priority request for a subsequent image of the target to study the evolving phenomena. In this case, CASPER modifies 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.

V. Onboard Robust Execution

ASE uses the Spacecraft Command Language (SCL)¹ 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, which is part of SCL, 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 or 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 are 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 as messages on the software bus.

Many aspects of autonomy are included in SCL. For example, SCL implements many constraint checks that are redundant with those in the EO-1 fault protection software. Before SCL sends each command to the EO-1 command processor, 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 also verifies that there is sufficient power so that the command does not trigger a low bus voltage condition and that there is sufficient energy in the battery. Using SCL to check these constraints and including them in the CASPER model provides an additional level of safety to the autonomy flight software.

VI. Space Science Extensions of ASE

The science component of the ASE software is being used onboard the Mars Exploration Rovers (MER) Mission to enable onboard detection and summarization of atmospheric events. Recent Mars explorations have revealed an environment far more active than previously believed. Dust devils and clouds are two examples of dynamic atmospheric features that have been observed by the MER. These scientifically interesting events have been the subject of considerable study. Both dust devil and cloud detection campaigns have been conducted, but in general these are rare events. For example, only around 10-25% of the cloud campaign images collected have clouds in them. Prior campaigns have involved collecting images at fixed times for return to Earth. This is an inefficient use of downlink bandwidth as the majority of images do not contain dust devils or clouds.

To improve the effectiveness of atmospheric imaging campaigns, we have developed a different approach. In this approach onboard processing is used to screen images for the science features of interest (i.e., clouds and dust devils). Using this approach, many images can be collected onboard resulting in a much greater time range for capturing the rare phenomena. Even when the images cannot be down-linked (such as when too many events are detected), compact summary statistics on the number and type of events can still be down-linked to provide valuable information. The code has been integrated with the MER flight software and has been uploaded and running since December 2006.

The science component of the ASE software is also under development for the Mars Odyssey Mission to enhance science return from the THEMIS instrument with operational capability later in the extended mission. In this application, the ASE software will:

- Track the seasonal variation in the CO₂ ice caps
- Detect thermal anomalies
- Track dust storms
- Track Martian clouds

The MER THEMIS instrument is powered on almost 100% of the time although only 5% of the data is collected due to bandwidth limitations. Using the ASE science algorithms, the THEMIS images can be analyzed onboard for the existence of thermal anomalies, dust storms, and clouds. Only the images that contain these events will be returned to Earth. This will allow the Odyssey Science Team to make use of the other 95% of the data that is currently lost. Detecting thermal anomalies would be a very low probability event but of very high science worth. Also, the boundaries of the CO₂ ice caps can be detected and only the image of the boundary will be returned.

In addition, we are researching autonomous science and sensorweb applications for magnetosphere events for space weather, change detection on Io and Europa, and storm tracking on Jupiter.

VII. The EO-1 Sensorweb

The use of automated planning onboard EO-1 has enabled a new system-of-systems capability. We have networked the EO-1 satellite with other satellites and ground sensors. This network is linked by software and the Internet to an autonomous satellite observation response capability. (See Figure 4.) This system is designed with a flexible, modular architecture to facilitate expansion in sensors, customization of trigger conditions, and customization of responses.

The EO-1 sensorweb has been used to implement a global surveillance program of science phenomena including: volcanoes, flooding, cryosphere events, and atmospheric phenomena. Using this architecture, we have performed over 700 sensorweb initiated satellite observations using EO-1. The automated retasking element of the sensorweb consists of several components working together as follows.

1. Science agents for each of the science disciplines automatically acquire and process satellite and ground network data to track science phenomena of interest. These science agents publish their data automatically to the internet each in their own format. In some cases this is via the http or ftp protocol, in some cases via email subscription and alert protocols.
2. Science agents either poll these sites (http or ftp) to pull science data or simply receive email notifications of ongoing science events. These science agents produce “science event notifications” in a standard XML format which are then logged into a “science event” database.
3. The science event manager processes these science event notifications and matches them up with particular science campaigns as defined by the scientists. When a match occurs, an observation request is generated.
4. These observation requests are processed by the ASPEN automated mission planning system. ASPEN integrates these requests and schedules EO-1 observations according to priorities and mission constraints.
5. For observations that are feasible, an observation request is uplinked to the spacecraft.

6. Onboard EO-1 the ASE software will accommodate the observation request if feasible. In some cases onboard software may have additional knowledge of spacecraft resources or may have triggered additional observations, so some uplinked requests may not be feasible.
7. Later, the science data is downlinked, processed, and delivered to the requesting scientist.

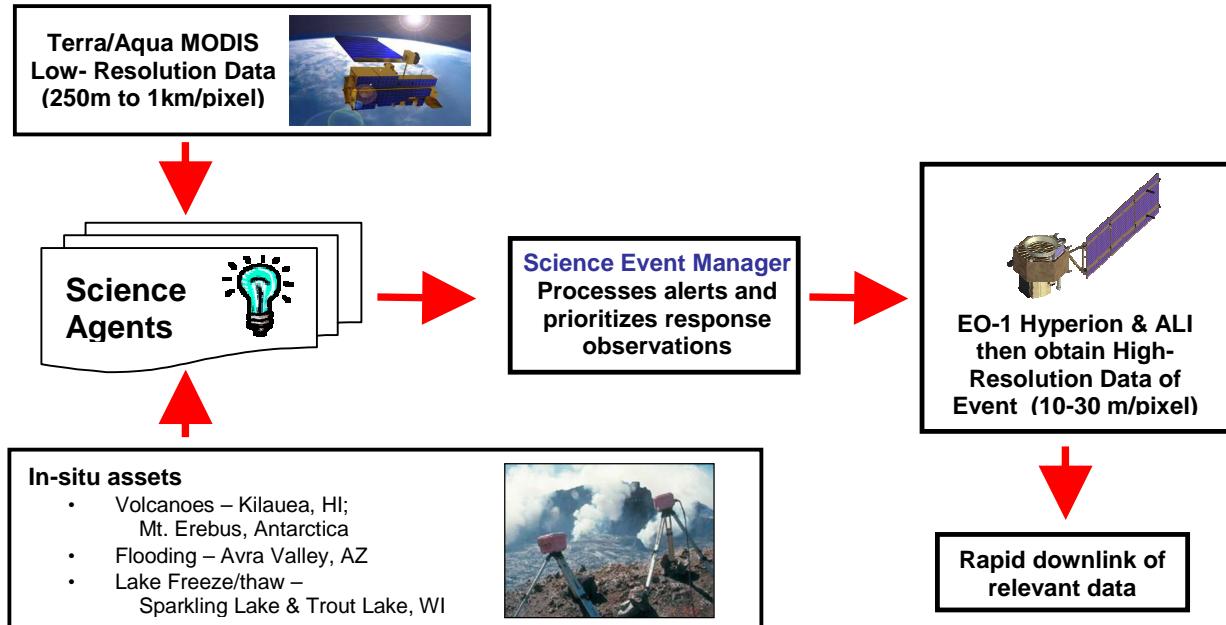


Figure 4. Sensorweb Detection and Response Architecture

A. Science Agents

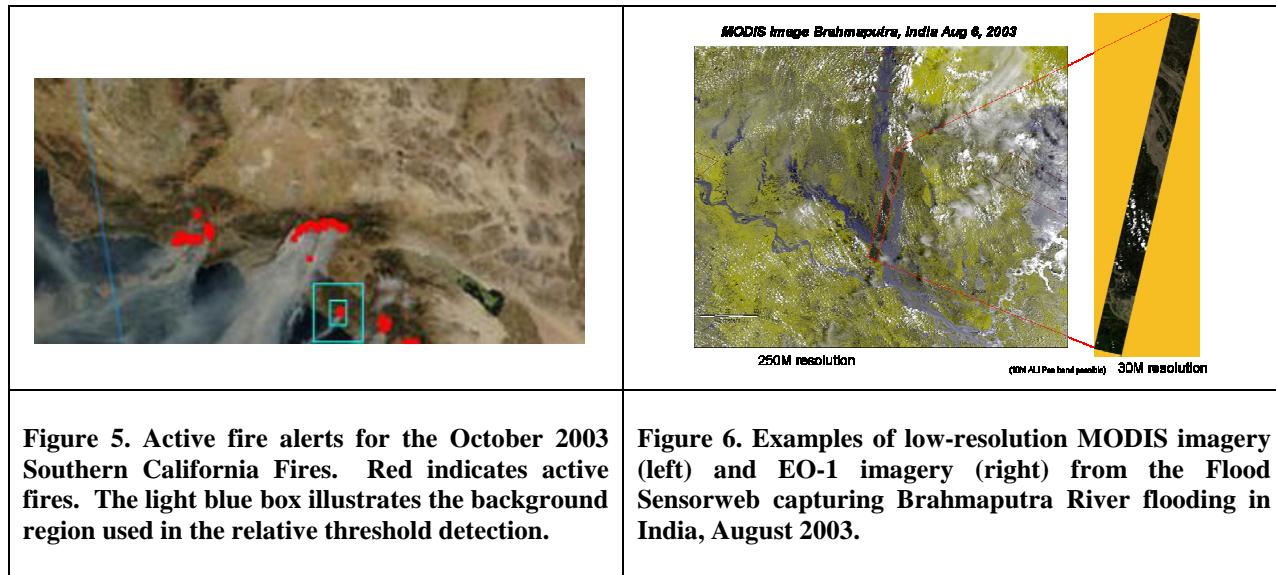
The science agents encapsulate sensor and science tracking specific information by producing a generic XML alert for each “science event” tracked. The flexibility enabled by these modules allows us to easily integrate with a large number of existing science tracking systems despite the fact that each science tracking system has its own unique data and reporting format. The data formats range from near raw instrument data, to alerts in text format, to periodic updates to a wide range of text formats. The posting methods include http, https, ftp, and email.

B. Science Event Manager and Science Campaigns

The Science Event Manager enables scientists to specify mappings from science events to observation requests. It enables them to track frequency and the number of events as well as perform logical processing. It also enables them to track based on target names or locations, and other event specific parameters (for example, some tracking systems produce a confidence measure). As an example, a volcanologist might specify for the Kilauea site that several tracking systems would need to report activity with high confidence before an observation is requested. This is because Kilauea is quite often active. On the other hand, even a single low confidence activity notification might trigger observation of Piton de la Fournaise or other less active sites.

C. The Wildfire Sensorweb

We have demonstrated the sensorweb concept using the MODIS active fire mapping system. Both the Terra and Aqua spacecraft carry the MODIS instrument, providing morning, afternoon, and two night over-flights of each location on the globe per day (coverage near the poles is even more frequent). The active fire mapping system uses data from the GSFC Distributed Active Archive Center (DAAC), specifically the data with the predicted orbital ephemeris which is approximately 3-6 hours from acquisition. Figure 5 shows the active fire map from October 2003 fires in Southern California.



D. The Flood Sensorweb

The flood sensorweb uses the Dartmouth Flood Observatory (DFO) Global Active Flood Archive to identify floods in remote locations automatically based on satellite data. The DFO flood archive publishes web-based flood alerts based on MODIS, QuikSCAT, and AMSR-E⁶ satellite data. The flood sensorweb utilizes the DFO QuikSCAT atlas because it is not affected by cloud cover over flooded areas.

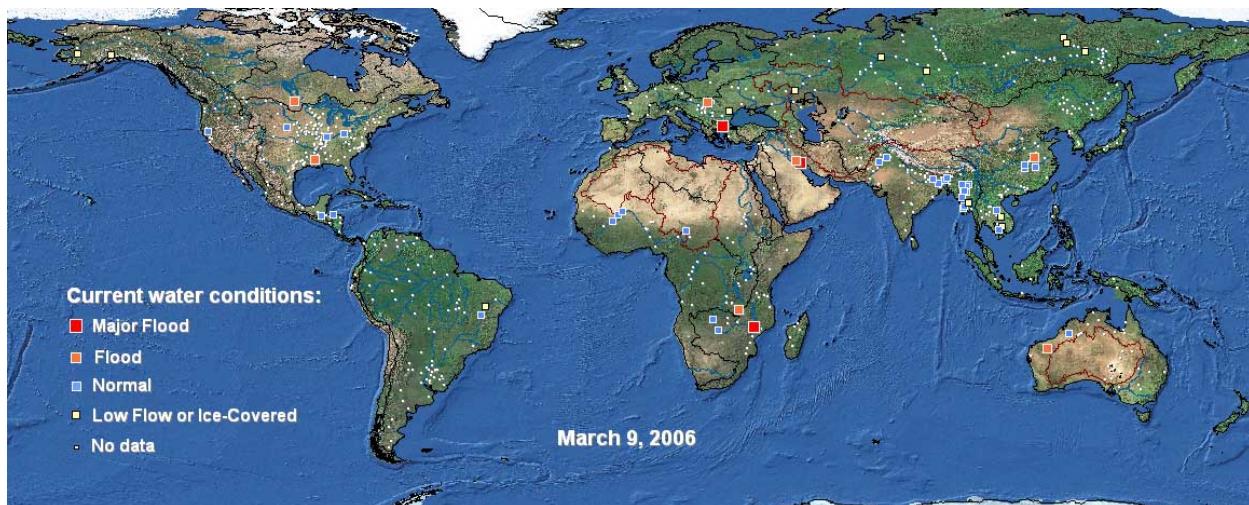


Figure 7. Dartmouth Flood Observatory Global Flood Alerts for March 2006.

In the flood sensorweb, active flooding alerts can trigger EO-1 observations at gauging reaches. Gauging reaches are river locations whose topography is well understood. Flood discharge measurements at gauging reaches can be used to measure the amount of water passing through a flooded region and can be compared with remotely sensed data. The end effect of the flood sensorweb is to increase the amount of high resolution remote sensing data available on flooding events in prime locations of interest (e.g., gauging reaches) and times of interest (e.g. when active flooding occurs). Imagery from an August 2003 flood sensorweb demonstration capturing flooding in the Brahmaputra River, India, is shown in Figure 6. An example of the DFO Flood Map is shown in Figure 7.

E. The Volcano Sensorweb

In the volcano sensorweb, MODIS, GOES7, and AVHRR sensor platforms are utilized to detect volcanic activity. These alerts are then used to trigger EO-1 observations. The EO-1 Hyperion instrument is ideal for study of volcanic processes because of its great sensitivity range in the infra-red spectrum.

The GOES7 and AVHRR alert systems provide excellent temporal resolution and rapid triggering based on thermal alerts. The GOES-based system looks for locations that are: hot, is high contrast from the surrounding area, and not visibly bright. Additionally, hits are screened for motion (to eliminate cloud reflections) and persistence (to remove instrument noise). The GOES alert can provide a web or email alert within 1 hour of data acquisition.

We have also linked into in-situ sensors to monitor volcanoes. The Hawaiian Volcano Observatory (HVO) has deployed numerous instruments on the Kilauea region in Hawaii. These instruments include tiltmeters, gas sensors, and seismic instrumentation. These sensors can provide indications that collectively point to a high-probability, near-term eruption thereby triggering a request for high-resolution, EO-1 imagery. The University of Hawaii has also deployed infra-red cameras⁸ to a number of volcanic sites worldwide (e.g., Kilauea, Hawaii; Erte Ale, Ethiopia; Sourfriere Hills, Montserrat; Colima and Popocatepetl, Mexico). These infra-red cameras can provide a ground-based detection of lava flows based on thermal signatures, thereby alerting the sensorweb.

F. Cryosphere Sensorweb

Many freeze/thaw applications are also of interest. This includes the phenomena of glacial ice breakup, sea ice breakup, melting, and freezing, lake ice freezing and thawing, and snowfall and snowmelt. Using QuikSCAT data we are tracking snow and ice formation and melting and automatically triggering higher resolution imaging using EO-1.

In collaboration with the Center for Limnology of the University of Wisconsin at Madison, we have linked into data streams from the Trout Lake station to use temperature data to trigger imaging of the sites to capture transient freezing and thawing processes.

VIII. Future Research in Earth-based Sensor Webs

A. Enabling Model Interactions in Sensor Webs

Current research in sensor webs is focusing on multiple aspects of the coordinated sensing problem. One area of research is enabling model interactions in sensor webs. This area is focused on the creation and management of new sensor web enabled information products. Specifically, the format of these data products and the sensor webs that use them must be standardized so that sensor web components can more easily communicate with each other. This standardization will allow new components such as models and simulations to be included within sensor webs. Some of the research topics being addressed are:

- Interoperable data ingest as well as easy plug-and-play structure for scientific algorithms;
- Data input from emerging grid and web common languages input such as the Open Geospatial Consortium (OGC) SensorML;
- Flexible hardware interfaces that can adapt to rapidly-changing data ingest protocols as well as ever-evolving algorithms;
- Connections to major spacecraft schedulers and task managers; and
- Semantic metadata to enable the transformation and exchange of data as well as data fusion.

The QuakeSim⁹ project at JPL, is applying a sensor web system to understand and study active tectonic and earthquake processes. Earthquake studies could be considered a classic case of a sensorweb, with distributed seismic sensors that are coordinated in the study of a scientific process. But studying earthquakes is considerably more complex than just a network of seismic sensors. QuakeSim integrates both real-time and archival sensor data with high-performance computing applications for data mining and assimilation. The computing applications include finite element models of stress and strain, earthquake fault models, visualization, pattern recognizers, and Monte-Carlo earthquake simulations. (See Figure 8.) The data sources include seismic sensors, GPS sensors for surface deformation, and spaceborne sensors such as interferometric synthetic aperture radar (InSAR).

The QuakeSim team is developing simulation and analysis tools to study the physics of earthquakes using state-of-the-art modeling, data manipulation, and pattern recognition technologies. This includes developing clearly defined accessible data formats and code protocols as inputs to the simulations. These codes must be adapted to high-performance computers because the solid Earth system is extremely complex and nonlinear, resulting in computationally intensive problems with millions of unknowns. Without these tools it will be impossible to

construct the more complex models and simulations necessary to develop hazard assessment systems critical for reducing future losses from major earthquakes.

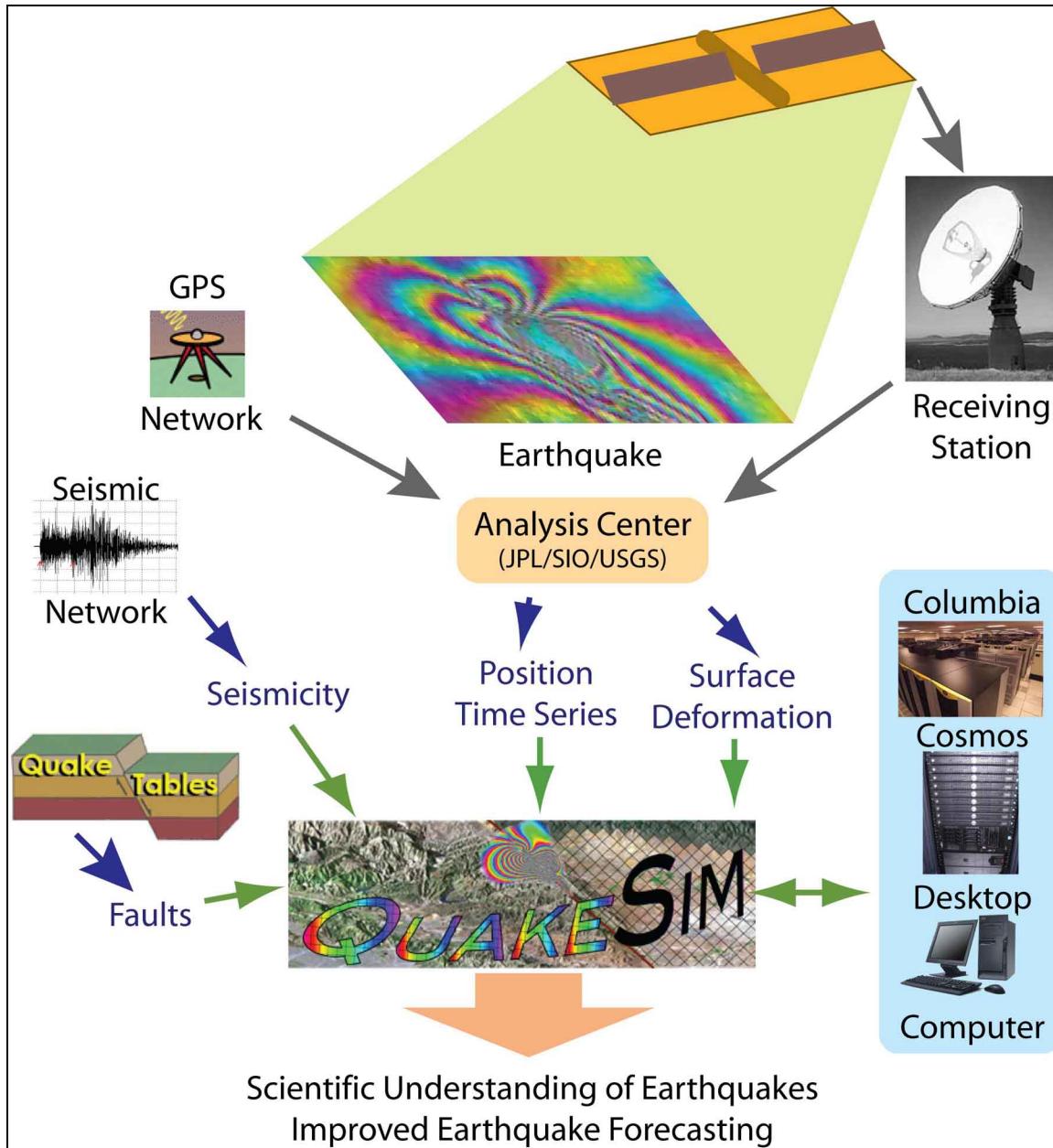


Figure 8. QuakeSim Architecture

B. Smart Autonomous Sensors

Another research area in sensor webs is smart sensing. Smart sensing implies sophistication in the sensors themselves. The goal of smart sensing is to enable autonomous event detection and reconfiguration. Research areas include:

- Communication of the sensor with the system, including interfacing with certain system protocols and sensor addressability, in which sensors can identify themselves and interpret selective signals from the system, providing output only on demand.
- Diagnostics to inform the system of an impending failure or to signal that a failure has occurred, as well as self-healing sensors.

- On-board processing (up to and including science data products, as appropriate), self-describing sensor languages and actuation logic.

1. Change Detection On-Board Processor (CDOP)

One existing smart sensing project is the On-Board Processor for Direct Distribution of Change Detection Data Products. CDOP is developing an autonomous disturbance detection and monitoring system for imaging radar that combines the unique capabilities of imaging radar with high throughput onboard processing technology and onboard automated response capability based on specific science algorithms.

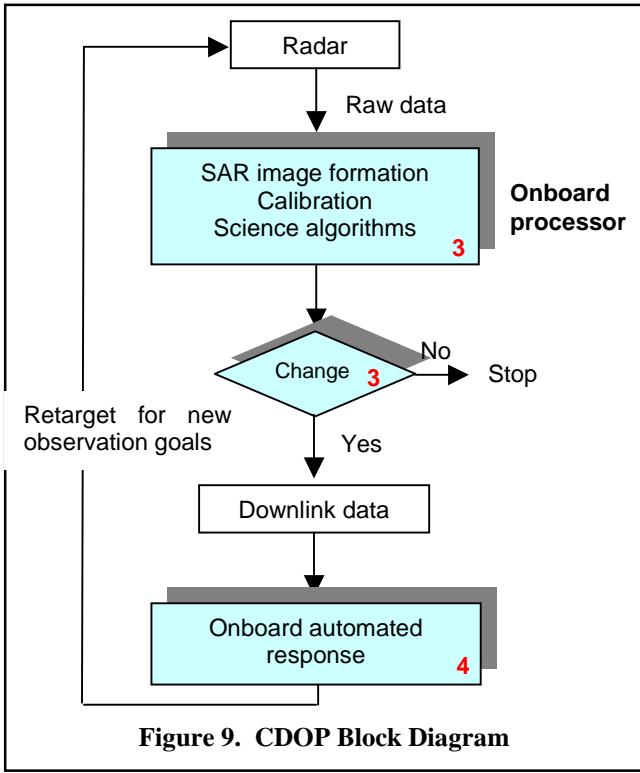


Figure 9 contains a block diagram of CDOP. Raw data from the radar observation are routed to the onboard processor via a high-speed serial interface. The onboard processor will perform SAR image formation in real time on two raw data streams, which could be data of two different polarization combinations or data from two different interferometric channels. The onboard processor will generate real-time high resolution imagery for both channels. The onboard processor will also execute calibration routines and science algorithms appropriate for the specific radar application. Autonomous detection is performed by an intelligent software routine designed to detect specific disturbances based on the results of science processing. If no change is detected, the process stops and the results are logged. If “change” due to specific disturbances is detected, the onboard automated response software will plan new observations to continue monitoring the progression of the disturbance. The new observation plan is routed to the spacecraft or aircraft computer to retarget the platform for new radar observations.

The CDOP team is also developing interfaces to existing sensor webs to conduct autonomous observation of specific science events based on external triggers from other sensors in the sensor web.

This smart sensor technology has the potential to provide key information for disaster and hazards management in the event of an earthquake, volcanic eruption, landslide, flood, and wildfire.

2. Optimized Autonomous Space - In-situ Sensor-web (OASIS)

Another smart sensing project is the Optimized Autonomous Space - In-situ Sensor-web (OASIS), a prototype real-time system composed of a ground segment and a space segment integrated through unified command and control software, with a focus on volcano hazard mitigation and with the goals of:

- Integrating complementary space and in-situ elements into an interactive, autonomous sensor-web
- Advancing sensor-web power and communication resource management technology
- Enabling scalability and seamless infusion of future space and in-situ assets into the sensor-web

The OASIS prototype will provide scientists and decision-makers with a tool composed of a “smart” ground sensor network integrated with “smart” space-borne remote sensing assets to enable prompt assessments of rapidly evolving geophysical events in a volcanic environment. The system will constantly acquire and analyze both geophysical and system operational data and make autonomous decisions and actions to optimize data collection based on scientific priorities and network capabilities. The data will also be made available to a science team for interactive analysis in real time. A typical science team is composed of a multidisciplinary group of vulcanologists that includes geodesists, remote sensing scientists, seismologists, geologists and gas geochemists.

The OASIS smart sensor capability will use space-based, and in-situ sensors, working together in a semi-closed loop system that feeds information into a control system, to make operation decisions “on-the-fly”. OASIS will demonstrate this complete ground-space operation scenario from the crater and flanks of Washington State’s Mount St. Helens. (See Figure 10.)

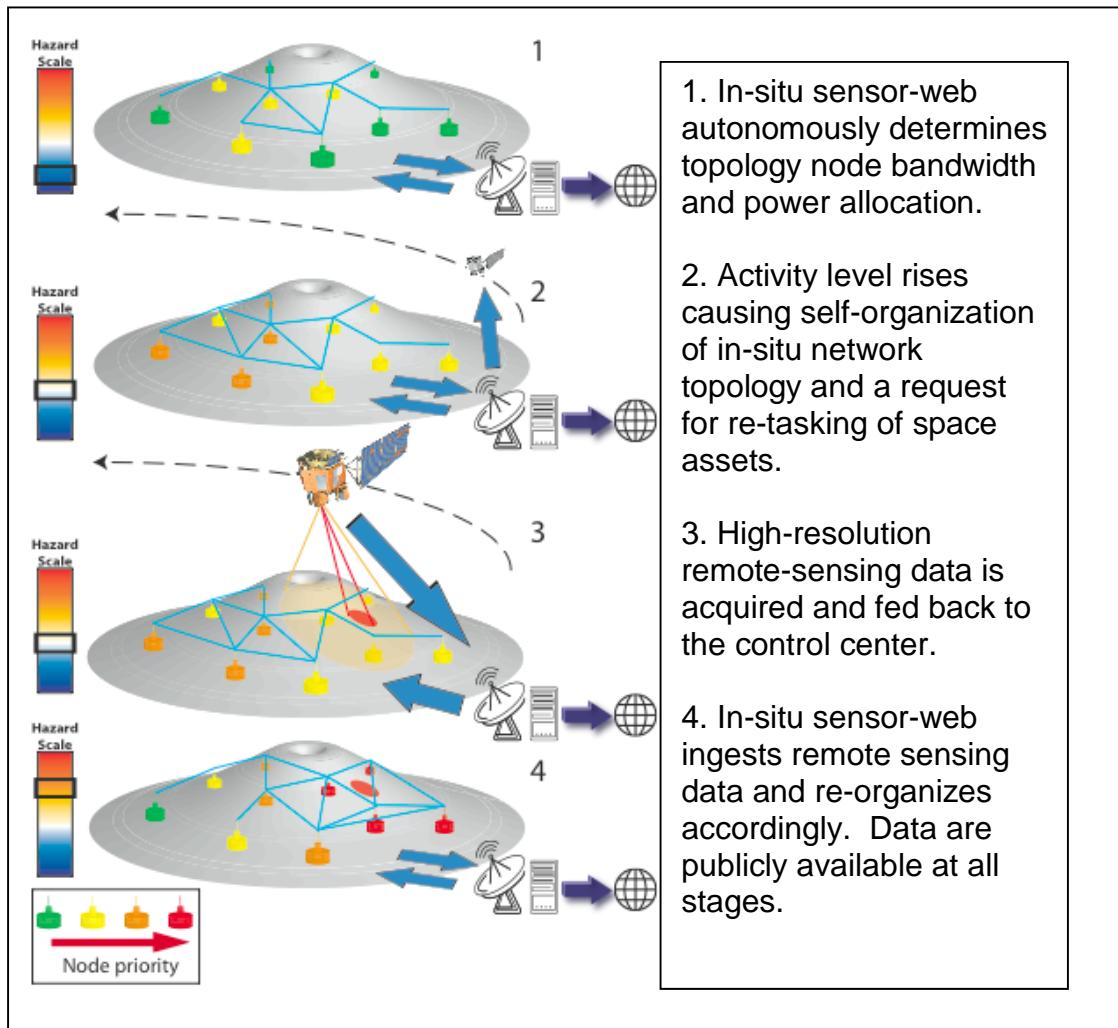


Figure 10. OASIS Concept

C. Sensorweb Communications

Another important area of sensor web research is communications technology. The goal of communication enhancements, especially session layer management, is to support dialog control for autonomous operations involving sensors and data processing and/or modeling entities. Specifically, research is being performed in the following areas:

- Adaptive and directive beam-forming antennas that can track the dynamic movement of sensor platforms;
- Autonomous networks and protocols that can distribute data communication tasks among the sensors and control the flow of data;
- Transmission schemes that maximize data throughput and provide optimum use of assigned bandwidth; and
- Distributed network of storage devices that can be accessed by any node in the sensor web with minimum latency.

1. Satellite Sensornet Gateway

One research project in sensor web communications is the Satellite Sensornet Gateway (SSG). SSG is an open and scalable sensor net gateway that provides storage and aggregation of data from wireless sensors, reliable transmission to a central data store, and sensor instrument management and control. The goals of SSG is to simplify sensornet design by isolating common communication and management functions into a flexible, extensible component that can be dropped into any in-situ sensornet, thus enabling new observation systems and datasets. The result is that in-situ sensors will become easier to deploy and manage, expanding their use by Earth scientists.

The overall system consists of three components: the SSG itself, the supported sensors, and the user interface. The SSG acquires, tags, stores, and transports data; collects and reports status; and receives and forwards commands. The system may also include local wireless connectivity in cases where the sensor and satellite terminal may not be easily collocated, say due to satellite visibility. The gateway will be implemented using a low-powered processor and is meant for unattended operation in the field. The SSG has interfaces to sensors and the network. Eventually SSG will support a wide variety of sensors and network technologies, selected either by the experimenter at deployment or dynamically based on external conditions. The gateway will make management information available to the user, e.g., system health or connection status. Sensor metadata will be used to de-multiplex aggregated data upon arrival at the NOC and provide context for data interpretation.

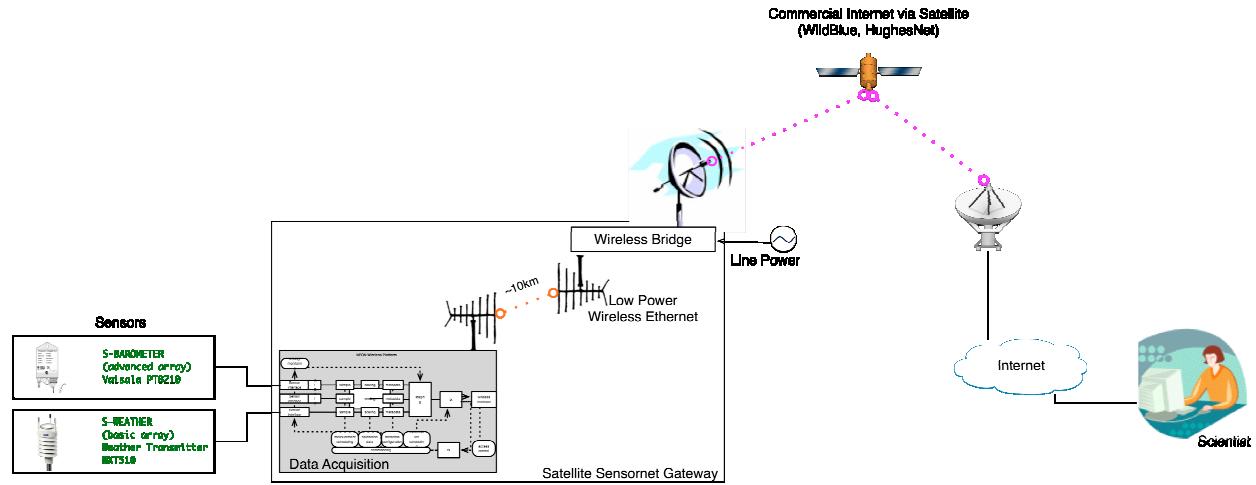


Figure 11. Satellite Sensornet Gateway (SSG)

Data arriving at the SSG will be tagged with standard metadata, such as GPS-sourced time and location. If sensors do not generate sufficient metadata to identify the specific instrument that sourced the data, the SSG will tag this as well. The choice of which metadata is used will be configurable based on user commands. The sensornet gateway will accumulate data from up to dozens of attached sensors, tag the data with meta-data, and schedule the data for delivery over a long-haul network to the NOC. The data may not be able to be immediately transmitted either due to scheduled link unavailability, link outages (e.g., weather), equipment failure, or data generation in excess of link capacities. SSG will include delay tolerant network (DTN) infrastructure to overcome difficulties in communications. The gateway will maintain sufficient non-volatile storage for several days without connectivity.

The gateway will monitor the status of attached nodes and forward it, on-demand and/or on-schedule, to the NOC. Status might include power margins, results of diagnostics, and failure reports. The SSG will also relay commands received from the NOC to the attached sensors. The gateway will be capable of being self-powered, via solar panels and batteries, and supplying some power to attached sensors. It will maintain its current location using GPS and will be designed taking environmental effects into account, e.g., weather-, salt-water-, or fire-resistant packaging and connectors.

2. Efficient Sensor Web Communication Strategies Based on Jointly Optimized Distributed Wavelet Transform and Routing (ESCOMS)

Another research project in sensor web communications is the Efficient Sensor Web Communication Strategies Based on Jointly Optimized Distributed Wavelet Transform and Routing (ESCOMS) project. ESCOMS is developing algorithms for configuring a sensor network topology and for efficiently compressing the correlated measurements as data is shipped toward a central node, so as to minimize energy consumption while reproducing the underlying field as accurately as possible. This system enables the nodes to reconfigure the network automatically, taking into account variations in the node characteristics (node mobility, power consumption, addition of new sensors, and deletion of other sensors).

ESCOMS will implement advances in compression including entropy coding, filter optimization, path merging, joint compression and routing, and temporal coding. Advances in networking and routing will include techniques in node selection, network initialization, routing optimization, link quality robustness, inclusion of broadcast nodes,

and automatic reconfigurability. These new capabilities are being tested in a lab and in a sensor web of about 100 nodes. Eventually they will be tested in an outdoor realistic environment for an extended period of time.

One ESCOMS scenario is the use of an in situ sensor web to monitor conditions and changes in the Antarctic ice shelf. Data collected from such a sensor web would be used in conjunction with a larger sensor web including airborne and spaceborne instruments. A second scenario that would benefit from ESCOMS is an in situ sensor web to monitor ecological conditions in a remote region such as a forest or a desert. ESCOMS is a great example of the use of autonomous networks and protocols, as well as optimized transmission schemes, which can be used in remote power-constrained Earth monitoring sensor webs.

IX. Summary

ASE on EO-1 demonstrates an integrated autonomous mission using onboard science analysis, replanning, and robust execution. The ASE performs intelligent science data selection that leads to a reduction in data downlink. In addition, the ASE increases 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 and has opened the doors to including spacecraft instruments in reactive sensor webs. The paradigm shift toward highly autonomous spacecraft will enable future NASA missions to achieve significantly greater science returns with reduced risk and reduced operations cost. We have also described ongoing work to link an automated science event tracking system with an autonomous response capability based on automated planning technology. Demonstration of these sensorweb capabilities will enable fast responding science campaigns and increase the science return of spaceborne assets. Future research in sensor webs will allow model and simulation driven sensors. Autonomy capabilities are being developed for sensors to allow them to interact with other sensors. Research in communications is improving the ability to deploy sensor webs in new areas inexpensively.

Acknowledgments

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 Ashley Davies, Daniel Tran, Gregg Rabideau, Rebecca Castaño, Andrea Donnellan, Yunling Lou, Sharon Kedar, Sam Dolinar, and Aaron Kiely of JPL, Dan Mandl, Stuart Frye, Seth Shulman, and Stephen Ungar of GSFC, Ronald Greeley and Thomas Doggett of Arizona State University, Victor Baker and James Dohm of the University of Arizona, Aaron Falk of USC ISI, and Antonio Ortega of USC.

References

-
- ¹ Interface and Control Systems, SCL Home Page, sclrules.com
- ² 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)
- ³ Goddard Space Flight Center, EO-1 Mission page: <http://EO-1.gsfc.nasa.gov>
- ⁴ M. Griffin, H. Burke, D. Mandl, & J. Miller, "Cloud Cover Detection Algorithm for the EO-1 Hyperion Imagery," Proceedings of the 17th SPIE AeroSense 2003, Orlando, FL, April 21-25, 2003.
- ⁵ 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.
- ⁶ S. V. Nghiem, W. T. Liu, and X. Xie, "Polarization Reversal over Flooded Regions and Applications to Flood Mapping with Spaceborne Scatterometers," International Geoscience and Remote Sensing Symposium, Hamburg, Germany, June 28 - July 2, 1999.
- ⁷ Harris, A. et al., (2002) Web-Based Hot Spot Monitoring using GOES: What it is and How it Works, Advances in Environmental Monitoring and Modelling Vol. 1 No. 3 (2002) pp.5-36.
- ⁸ Harris et al., Ground-based Infrared Monitoring Provides New Tool for Remote Tracking of Volcanic Activity, EOS, Vol. 84, No. 40, 7 October 2003
- ⁹ A. Donnellan, J. Parker, C. Norton, G. Lyzenga, M. Glasscoe, G. Fox and M. Pierce, J. Rundle, D. McLeod, L. Grant, W. Brooks, T. Tullis, "QuakeSim: Enabling Model Interactions in Solid Earth Science Sensor Webs," Proceedings of 2007 IEEE Aerospace Conference, Big Sky, MT, March 2007.