# Sensor Web Technologies: A New Paradigm for Operations

Rob Sherwood(1) and Steve Chien(1)
(1) Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA, 91109, USA,
Rob.Sherwood@jpl.nasa.gov

**ABSTRACT**

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. 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 software has also enabled EO-1 to link 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. These sensor webs will be operated directly by scientists using science goals to control their instruments.

## 1. INTRODUCTION

The operation of spacecraft has evolved considerably over the past decade with the inclusion of autonomy both on the ground and on the spacecraft. Starting with the Remote Agent Experiment in 1999, followed by the EO-1 Autonomous Sciencecraft (ASE) in 2004, autonomy has changed the way we perform mission planning, sequencing, and science discovery. These changes were enabled by higher performance computers that allow complex planning and reasoning software to migrate on to the spacecraft. This onboard autonomy allows a spacecraft to be directed by goals rather than detailed commands and sequences where every step has to be defined in advance. This same autonomy is being used in ground sensor networks to increase coordination between sensor assets. These autonomous sensor networks, or sensor webs, rely on a new generation of operations tools and procedures that link the scientist directly with the instruments/sensors.

## 2. GOAL DIRECTED SPACECRAFT

Autonomy software combined with increasingly complex spacecraft have changed the manner in which we control our missions. New missions have included mobile robots and distributed sensor networks that are interacting with dynamic and unknown environments. The typical method of controlling a mission is to send detailed commands specifying how to accomplish a particular science or engineering goal. Recent research and prototype operations have used *goal directed spacecraft (GS)*, where the operator will specify what to accomplish rather than how to accomplish it. [1] Using a GS allows a complex system to select among alternatives for achieving a goal. The GS includes a spacecraft model of resources, flight and operations constraints, and goals to be achieved.

Advantages of GS include reducing the operations complexity of the mission. Modern missions have far too many states and transitions between states to test, verify, and operate. Missions can be more resilient to anomalies by trying alternatives rather than safing during anomalies. Goals are much more intuitive to operators than long command sequences. GS are more adept at dealing with unknown or uncertain environments. Lastly, GS are more efficient because they close the loop on spacecraft control.

## 3. WHAT IS A SENSOR WEB?

Currently there is no universal understanding about what comprises a sensor web, although there are many related concepts that hopefully will evolve into a broadly accepted lexicon. Other terms such as sensor network and system-of-systems have been used interchangeably with sensor web. Some examples of sensor webs include the seismic GPS network, the A-Train constellation of satellites, and the tsunami early warning system. Each of these examples has varying levels of integration, coordination, and autonomy. Recent publications have defined sensor webs as follows:

- A coherent set of distributed “nodes”, interconnected by a communications fabric, which collectively behave as a single, dynamically adaptive, observing system. (Talabac, GSFC)

- An interconnected "web of sensors" that coordinates observations by spacecraft, airborne instruments and ground-based data-collecting stations. Instead of operating independently, these sensors collect data as a collaborative group, sharing information about an event as it unfolds over time. (NASA press release)

Both of these are good definitions, but they don't really capture the idea of feedback between sensors to capture further measurements. As defined at the February 2007 NASA ESTO/AIST workshop on sensor web technologies [2], a sensor web is:

> A coordinated observation infrastructure composed of a distributed collection of resources that can collectively behave as a single, autonomous, task-able, dynamically adaptive and reconfigurable observing system that provides raw and processed data, along with associated meta-data, via a set of standards-based service-oriented interfaces.

Some key sensor web features include the ability to obtain targeted observations through dynamic tasking requests, the ability to incorporate feedback (e.g., forecasts) to adapt via autonomous operations and dynamic reconfiguration, and improved ease of access to data and information. Some key sensor web benefits include improved resource usage where selected sensors are reconfigured to support new science questions; improved ability to respond to rapidly evolving, transient phenomena via autonomous rapid reconfiguration, contributing to improved tracking accuracy; cost effectiveness which derives from the ability to assemble separate but collaborating sensors and data forecasting systems to meet a broad range of research and application needs; and improved data accuracy, e.g., through the ability to calibrate and compare distinct sensor results when viewing the same event.

## 4. THE EO-1 SENSORWEB

One example of how onboard autonomy has enabled a sensor web is the Autonomous Sciencecraft (ASE) running on the EO-1 spacecraft. The ASE 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 use of automated planning onboard EO-1 has enabled a sensor web capability. The EO-1 satellite has been networked with other satellites and ground sensors to form an autonomous satellite observation response capability [3]. The EO-1 sensorweb has been used to implement a global surveillance program of science phenomena including: volcanoes, flooding, cryosphere events, and atmospheric phenomena. 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. When the science agents discover a significant science event, the EO-1 satellite is automatically retasked to study the area of interest using its higher resolution instruments. Scientists can update the science agents based on specific scientific goals. In this case, the EO-1 satellite is being operated directly by scientists.

## 5. OPERATIONS IMPLICATIONS FOR AUTONOMY

When autonomy is added to a goal directed spacecraft, the science feedback loop can be moved from the ground to onboard the spacecraft. Typically, spacecraft operations involve acquiring instrument data, downlinking that data, analyzing the data, and then issuing new commands to the spacecraft to acquire more data based on the analysis. With autonomy onboard, the decision about what data to acquire next can be made by science agents. These science agents are directed with goals rather than detailed commands. The goals are expanded using planning software that has a model of the spacecraft resources and operating constraints. For non-autonomous spacecraft, operators would typically run detailed safety checks of spacecraft sequences and commands each week before upload. Using autonomous spacecraft, these checks only have to be performed once on the onboard spacecraft model. This greatly simplifies the ground planning process. It also allows the scientists to be more directly involved in the planning process. Scientists will select and submit observation goals directly to the flight control team for upload to the spacecraft. These goals will be integrated with spacecraft produced science goals and engineering goals from the spacecraft operations team. The onboard planning software will determine which goals are achievable.

Another way autonomy software is changing operations is anomaly resolution. Typically when a spacecraft experiences an anomaly, a safe hold mode will be entered to allow the spacecraft to remain safe until the ground operators can resolve the problem. Using an autonomous spacecraft, the planning software can still function with knowledge of the failed component. Since the components are modeled as resources, and the resources are used in achieving goals, the planner can just plan using the degraded state of the resource. In some instances, the planner can select alternative methods of achieving a goal that do not rely on the failed component.

## 6. 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.

#### *1. QuakeSim Project*

The QuakeSim [4] 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 1.) 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.

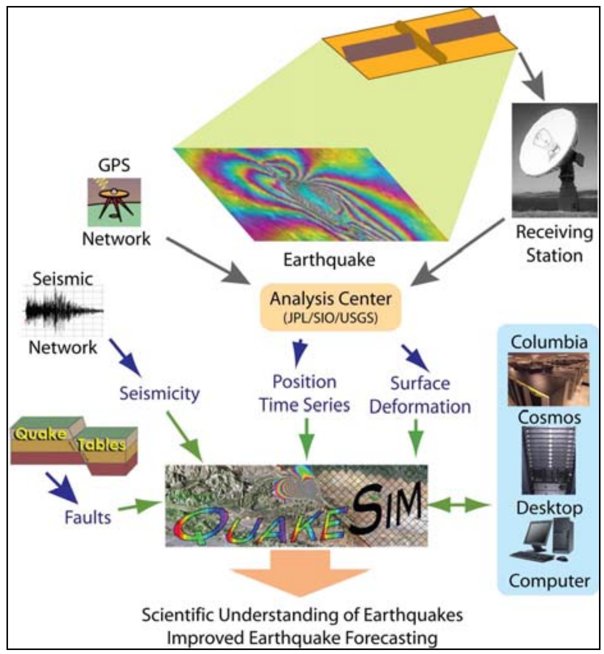


**Figure 1. QuakeSim Architecture**

#### *2. Semantically-Enabled Science Data Integration (SESDI)*

The goal of the SESDI [5] project is to bring together diverse sets of scientific data from three very different scientific disciplines such that researchers can access the data quickly and transparently, without having to understand the details of the sources of the data and the peculiarities of each individual data source. This type of measurement-based, as opposed to instrument-based, approach has the potential to greatly speed up interdisciplinary research that would normally require collecting many kinds of data from many different sources, then figuring out how to meld the various datasets into something consistent with respect to location, time, units, definitions, etc. Rather than forcing scientists to be data set curators, SESDI provides a significant step away from that paradigm. SESDI can be used in areas such as climate research that involve data from ground-based, airborne, and space borne instruments studying the Earth's atmosphere, oceans, land surface and ice cover, as well as the Sun and the response of the Earth system to solar activity. SESDI will allow scientists to focus on creative new investigations of climate change, without spending undue resources on collecting and integrating disparate data sources.

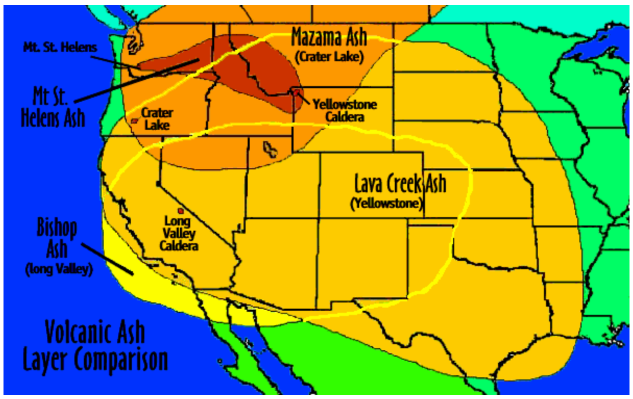


**Figure 2. Compilation of distribution of volcanic ash associated with large eruptions. Note the continental scale ash fall associated with Yellowstone eruption ~600,000 years ago.**

Data discovery and access has traditionally been done using the specific terminology of those who have a deep understanding of the data sources (instruments or model output), those who have developed the databases, and those who are expert in a specific discipline. Moving from this basic syntactic (instrument-based) approach to a higher level (measurement-based) semantic approach will also make data and higher-level information more accessible to a wider group of people. At the same time, the semantic metadata will allow for a transformation and exchange of measurement data from diverse sensors within a sensorweb. SESDI will also enable data fusion from diverse data sources within a sensorweb, which will be important for understanding complex scientific phenomena. One example is large volcanic eruptions. Geologic databases provide the information about the magnitude of the eruption, and its impact on atmospheric chemistry and reflectance associated with particulate matter requires integration of concepts that bridge terrestrial and atmospheric data sources. (See Figure 2.)

**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 [6]. 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 3 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

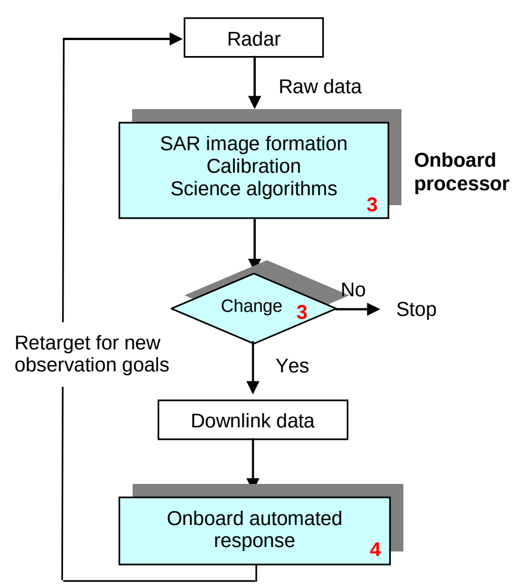


**Figure 3. CDOP Block Diagram**

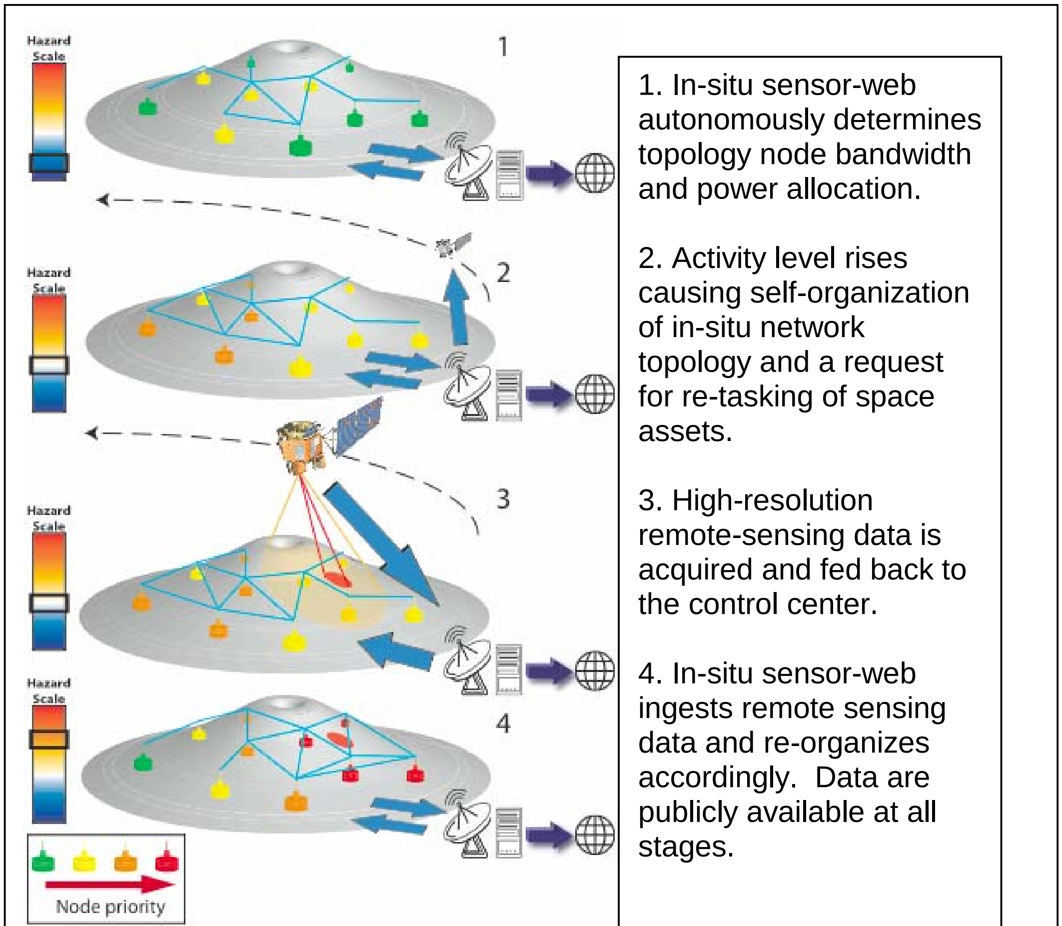


**Figure 4. OASIS Concept**

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" spaceborne 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 4.)

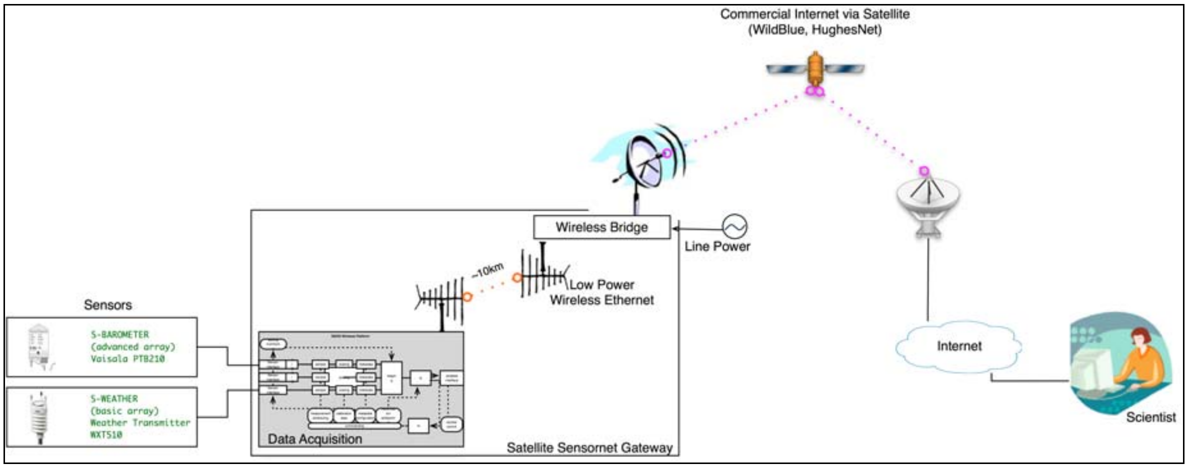


**Figure 5. Satellite Sensornet Gateway (SSG)**

### 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.

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.

## 7. CHALLENGES FOR MORE EFFECTIVE SENSORWEBS

Building more effective sensor webs involves many different challenges in the areas of information standardization and autonomy. These challenges are driven by the increasing complexity of sensor webs and the sensors within them.

The challenges in information standardization have evolved from the difficulty in the collection and analysis of information from many different types of sensors. For future sensor webs to operate more effectively, we need to develop standards on how to operate sensor webs, as well as a standard representation of sensor data. The Open Geospatial Consortium (OGC) is contemplating adoption of a technology called Web Processing Service (WPS), which is one step towards standards-based exposure of sensor data on the web [7]. This is a great step forward for accessing sensor data, but we need to create data standards so that the different sensor data and the models that use them can be fused together to answer complex scientific questions. Much of these data are in different spatial and temporal resolutions, but by combining them, we achieve greater spatial coverage and resolution than by analyzing any one sensor.

Another issue with data standardization is that end users of sensor data have insufficient technical expertise and time to extract information from the sensor data. This problem is being addressed with the evolving Earth science ontologies being created that will infuse meta data into the sensor data. This will allow data that can be filtered, summarized, and transformed, and will also allow features to be extracted into higher level features. In addition, the same data can be reused for different applications. Different users will be able to have different views of the sensor data depending on their particular needs.

Many of today's sensor webs employ little autonomy. The deployment and usage of sensors is usually tightly coupled with the specific location, application, and the type of sensors being used. Future science applications for sensor webs will require data from many different types of sensors and even integrating multiple sensor webs (sometimes referred to as a *system-of-systems*.) To be effective, this will require a capability for publishing and discovering sensor resources. Once this infrastructure is in place, it will be much easier to pull additional sensors into a particular sensor web application.

Operation of complex sensor web systems will require cooperation between different missions and agencies. For example, the EO-1 sensor web involved combining data from EO-1, Aqua, Terra, GOES, QuickScat, and several ground sensor networks. Operations organizations will require more flexibility because they will often be working with systems they don't control. One very complicated sensor web example requiring cooperation is the Global Earth Observing System of Systems (GEOSS). GEOSS is an agreement among 69 nations to share Earth science data and models to achieve comprehensive, coordinated and sustained observations of the Earth system, in order to improve monitoring of the state of the Earth, increase understanding of Earth processes, and enhance prediction of the behavior of the Earth system. The GEOSS architecture has a focus on open systems, standard interface, interoperable formats, service oriented architectures, and semantic data. The GEOSS vision will never be realized without significant cooperation at all levels (from operators and spacecraft developers to governments).

## 8. SUMMARY

The increase in onboard computing performance has enabled new levels of autonomy on spacecraft. This autonomy in turn has allowed spacecraft to be linked with Earth-based sensor networks. These ground networks have also been incorporating increased autonomy to form 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. 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, Dan Dvorak, Daniel Tran, Gregg Rabideau, Rebecca Castaño, Andrea Donnellan, Yunling Lou, Sharon Kedar, Sam Dolinar, and Aaron Kiely of JPL, Peter Fox of UCAR, Aaron Falk of USC ISI, Wen Zhan Song of WSU, and Antonio Ortega of USC.

## REFERENCES

[1] D. Dvorak, M. Ingham, R. Morris, and J. Gersh, "Goal-Based Operations: An Overview," AIAA Infotech 2007, Rohnert Park, CA, May 2007.

[2] NASA ESTO/AIST Sensor Web PI Workshop, URL: http://esto.nasa.gov/sensorwebmeeting/ , cited [12 June 2007], February 2007.

[3] R. Sherwood, S. Chien, D. Tran, A. Davies, R. Castano, G. Rabideau, D. Mandl, S. Frye, S. Shulman, J. Szwaczkowski, "Enhancing Science and Automating Operations Using Onboard Autonomy," The 9th International Conference on Space Operations, Rome, Italy, June 2006.

[4] 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.

[5] P. Fox, D.L. McGuinness, R. Raskin, A. Krishna Sinha. "Semantically-Enabled Scientific Data Integration," U.S.Geological Survey Scientific Investigations Report 2006-5201, p. (Geoinformatics 2006).

[6] Y. Lou,. S. Hensley, C. Le, D. Moller, "On-Board Processor for Direct Distribution of Change Detection," IEEE Radar Conference and Proceedings, Philadelphia, April 2004.

[7] Open Geospatial Consortium (OGC) page, URL: http://www.opengeospatial.org/standards/requests/28, cited [5 June 2007].