An Autonomous Earth Observing Sensorweb

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Abstract – *We describe a network of sensors linked by software and the internet to an autonomous satellite observation response capability. This system of systems is designed with a flexible, modular, architecture to facilitate expansion in sensors, customization of trigger conditions, and customization of responses.*

This system has been used to implement a global surveillance program of science phenomena including: volcanoes, flooding, cryosphere events, and atmospheric phenomena. In this paper we describe the importance of the earth observing sensorweb application as well as overall architecture for the system of systems.

Keywords: *Remote sensing, Spacecraft autonomy, artificial Intelligence.*

1 Introduction

In a remote area of southern Africa, lightning strikes grassland, sparking a local fire that rapidly spreads across the dry, grassy region. Overhead, the Terra & Aqua satellites, each using a MODIS instrument, acquire moderate resolution (250m-1000m/pixel) data of every point on the Earth twice per day. These data are streamed to the Rapidfire center at the University of Maryland and Goddard Space Flight Center where raw imagery is automatically classified into fire alerts within hours of acquisition. Software monitoring the Rapidfire web site matches this new alert with a previously specified science team interest in fires in this region and generates an observation request to the Earth Observing One (EO-1) Ground System. This observation request is processed within a ground system automation system for EO-1 to develop a command sequence to acquire the observation. After the commands are uplinked, at the appropriate time, the spacecraft slews and acquires the high resolution (pan-band up to 10m/pixel) image with hyperspectral (220+ bands) data for science analysis. This autonomous response has enabled detailed follow-up data on the science event of interest within 48 hours of the initial detection. Additionally, the science return of EO-1 is optimized by targeting known science events.

--The EO-1 sensorweb has demonstrated this and similar scenarios since its first operations in August 2003.

A wide range of operations satellite/platforms make their data freely available (e.g. broadcast or internet) in a rapid fashion (tens of minutes to several hours from acquisition). For example, data from the Moderate Resolution Imaging Spectrometer (MODIS) flying on Terra and Aqua are available via Direct Broadcast in near real-time for regional coverage and 3-6 hours from acquisition from the GSFC Distributed Active Archive Center (DAAC) (for global coverage). These data provides regional or global coverage with a wide range of sensing capabilities. For example, MODIS covers the globe roughly 4 times daily (two day and two night overflights). QuickSCAT covers the majority of the globe daily.

Unfortunately, these global coverage instruments do not provide the high resolution data desirable for many science applications. The above instruments range in resolution from MODIS with 250m-1km resolution to 1km and above for the other instruments. While ideally high resolution data would be available continuously with global coverage, typically high resolution assets can image only limited swathes of the Earth – thus making them highly constrained and high demand assete.

In this paper we describe initial efforts to network sensors and science event recognizers/trackers with an automated response system to form a sensorweb, defined as follows.

<u>Sensorweb</u> *A networked set of instruments in which information from one or more sensors is automatically used to reconfigure the remainder of the sensors*

Specifically, in our application, In our application we use low resolution, high coverage sensors to trigger

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1 - MitreTek, 2 - Honeywell.

observations by high resolution instruments. Note that there are many other rationales to network sensors into a sensorweb. For example automated response might enable observation using complementary instruments such as imaging radar, infra-red, visible, etc. Or automated response might be used to apply more assets to increase the frequency of observation to improve the temporal resolution of available data.

In the remainder of the paper we first describe our preliminary sensorweb efforts to track

- Volcanoes,
- Floods,
- Wildfires,
- Cryosphere events (Snowfall and melt, lake freezing and thawing, sea ice formation and breakup.

We also describe ongoing efforts to expand the sensorweb to other remote sensing and in-situ assets.

2 Sensorweb Scenario

The EO-1 sensorweb architecture consists of a number of components which operate in the following sequence of steps.

1. Asset1 acquires data (usually global coverage at low resolution)
2. Data from Asset1 is downlinked
3. This data is automatically processed to detect science events
4. Science event detections are forwarded to a re-tasking system. This system generates an observation request which is forwarded to an automated planning system.
5. This automated planning system then generates a command sequence to acquire the new observation.
6. This new command sequence is uplinked to Asset2 which then acquires the high resolution data.
7. This data is then downlinked, processed, and forwarded to the interested science team.

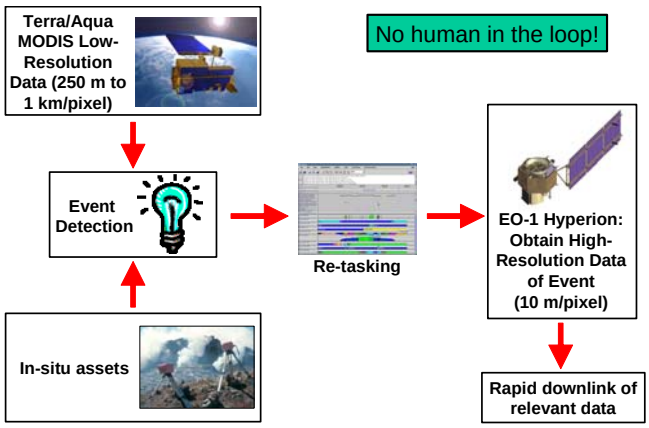

Figure 1. Sensorweb Detection and Response Architecture

In our operational system thus far Asset2 has been the Earth Observing One spacecraft (EO-1). EO-1 is the first satellite in NASA's New Millennium Program Earth Observing series. The primary focus of EO-1 is to develop and test a set of advanced technology land imaging instruments.

EO-1 was launched from Vandenberg Air Force Base 2000. Its orbit allows for 16-day repeat tracks, with 3 over flights per 16-day cycle at a less than 10-degree change in viewing angle. Because EO-1 is in a near polar orbit, polar targets can be viewed more frequently.

EO-1 has two principal science instruments, the Advanced Land Imager (ALI) and the Hyperion hyper spectral instrument. The ALI is a multi-spectral imager with 10m/pixel pan-band resolution and 9 spectral bands from 0.433 to 2.35 µm with 30m/pixel resolution. ALI images a 37km wide swath. The Hyperion is a high-resolution imager capable of resolving 220 spectral bands (from 0.4 to 2.5 µm) with a 30m/pixel spatial resolution. The instrument images a 7.5 km by 42 km land area per image and provides detailed spectral mapping across all 220 channels with high radiometric accuracy.

In the following sections of the paper we describe:

1. the sensorweb architecture;
2. the principal science detectors that have been implemented and ongoing efforts to extend the sensorweb to additional orbital and ground-based assets ; and
3. systems architecture design goals and lessons learned.

3 EO-1 Sensorweb Architecture

The automated retasking element of the sensorweb consists of several components working together as follows.

1. Science tracking systems for each of the science disciplines automatically acquire and process satellite and ground network data to track science phenomena of interest. These science tracking systems 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 emails to receive notifications of ongoing science events. These science agents then 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 « science campaigns ». 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 observations according to priorities and missionconstraints.
5. For observations that are feasible, an observation request is uplinked to the spacecraft.
6. Onboard EO-1 the Autonomous Sciencecraft software [Chien et al. 2004] will accomodate the observation request if feasible. In some cases onboard software may have additional knowledge of spacecraft resources or may have triggered additional obsrevations so some uplnked requests may not be feasible.
7. Later, the science data is downlinked, processed, and delivered to the requesting scientist.

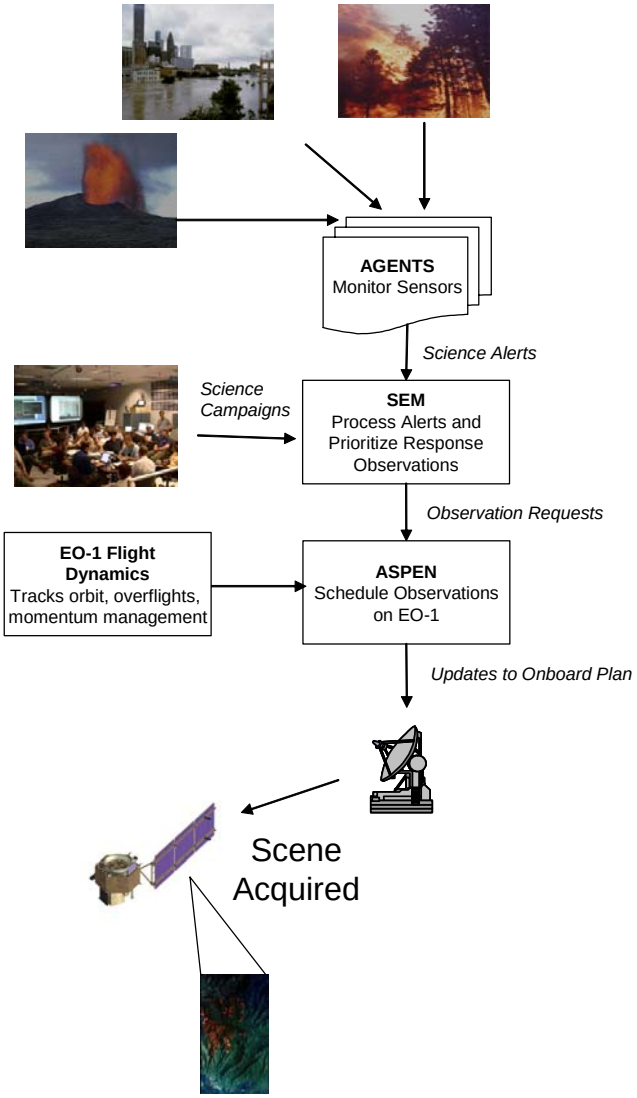

Figure 2. Sensorweb Response

3.1 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 enables by these modules has allowed use to easily integrate with a large number of science tracking systems despite the fact that each science tracking system has its own unique data and reporting format. These formats have ranged from near raw instrument data, to alerts in text format, to periodic updates to a wide range of text formats. The posting methods have included http, https, ftp, and email. Below we list the science tracking systems integrated into our system.

Discipline	Source	Detector
Volcanos	MODIS (Terra Acqua)	MODVOLC, U Hawaii
	GOES	GOESVolc
	POES	AVHRR - Volcano
	Air Force Weather Advisory	Volcanic Ash Alerts
	International FAA	Volcanic Ash Advisories
	Tungurahua, Reventador	In-situ instruments, Harvard, UNH
	Hawaiian Volcano Observatory, Rabaul Volcano Observatory, ...	Sensor alerts
Floods	QuikSCAT	Dartmouth Flood Observatory
	MODIS	Dartmouth Flood Observatory
	AMSR	Dartmouth Flood Observatory
Cryosphere	QuikSCAT (Nghiem)	Snow/Ice, JPL/Nghiem
	Wisconsin Lake Buoys	UW Dept. Limnology
Forest fires	MODIS (Terra, Acqua)	RAPIDFIRE, U. MD, MODIS Rapid Response
Dust Storms	MODIS (Terra, Acqua)	Naval research Laboratory, Monterey

Figure 3: Science Alert Systems

3.2 Science Event Manager and Science Campaigns

The Science event manager enables scientists to specify mappings from science events to observation requests. In enables them to track recency and count of events and do 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.

3.3 Automated Observation Planning

To automate mission planning we use the ASPEN/CASPER planning & scheduling system [Chien et al. 2000][2]. ASPEN represents mission constraints in a declarative format and searches possible mission plans for a plan that satisfies many observation requests (respecting priorities) and also obeys mission operations constraints. ASPEN has been used in a wide range of space mission

[2] ASPEN is the ground, batch planner, CASPER is the embedded, flight planner. Both share the same core planning engine.

applications [Chien et al 2000b] including spacecraft operations scheduling, rover planning, and ground communications station automation. Figure 4 shows the graphical user interface of an EO-1 operations plan.

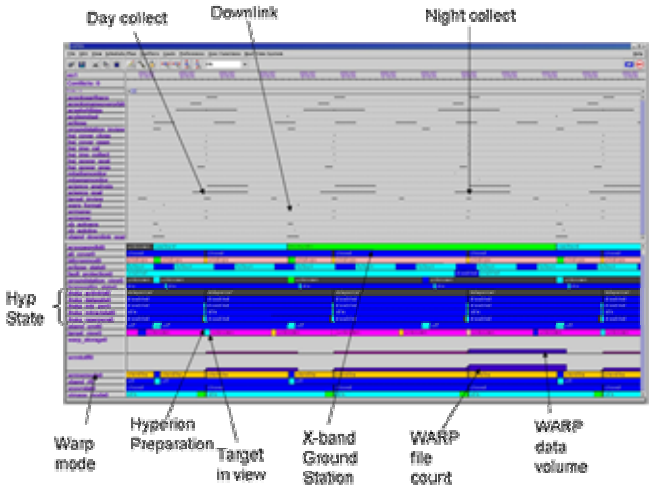

Figure 4: EO-1 Observation Plan as displayed by ASPEN GUI

3.4 Science Data Access

One of the design goals of the sensorweb project has been to provide scientists easy access to multiple data sources on a single science event (such as a volcanic eruption, forest fire,…). Unfortunately, the data access portal for the sensorweb project is still under construction.

As a related goal the sensorweb effort was also supposed to enable easy tracking of the spacecraft operations. This would enable scientists to understand the images the spacecraft had acquired and allow them to view where science products are in request, acquisition, downlink, and processing phases.

3.5 Sensorweb Architecture Design Considerations and Lessons Learned

When the sensorweb (SWB) was designed, several of the underlying systems already existed. Thus, in our design we utilized a system of systems approach, in which individual systems were designed or adapted to conform to logical abstract interfaces. For example, because deisng and deployment of a single science event tracking system might require millions of dollars, we wanted to leverage the wide range of existing science event tracking systems. This led to the creation of the science agent modules.

However, an appropriate means for assimilating event information and cross referencing it with scientists intent did not exist. This led to the science event manager and campaign builder development.

While EO-1 had an existing ground operations system, it did not easily support the level of automation desired for the SWB. Consequently, ASPEN was integrated into the ground operations system, requiring interfacing to EO-1 flight dynamics software and other ground support tools.

The SWB architecture was designed with several goals in mind. We review the design goals, how he design was to achieve these goals, and evaluate how well the sensorweb has achieved these goals thus far.

1. *Goal: SWB should enable easy access to a wide range of existing science tracking systems.* Design: utilize a very flexible architecture with customizable science agents to allow interface to a wide range of science tracking systems using a wide range of communications protocols. Evaluation: The SWB has been interfaced to numerous science tracking systems with minimal effort. These interfaces have been reliable and have survived evolution and updates to the underlying tracking systems.
2. Goal: *SWB should enable easy construction and modifications of science campaigns so that scientists can precisely specify their priorities and areas of interest.*
   Design: the science event manager allows scientists to specify science campaigns using a graphical user interface. Science campaigns can use a range of logical, threshold, and count fields to influence their campaigns.
   Evaluation: scientists have not specified complex campaigns and tend to not modify their campaigns frequently. Event the best of interfaces does not compare to an intelligent human.
3. Goal: The SWB should enable complete “lights out” automation so as to make rapid response imaging using EO-1 the norm rather than the exception. Design: each of the steps involved in the SWB architecture was designed to enable complete automation. The mission planning step, supported by ASPEN, is the most radical automation step. Evaluation: The overall automation flow has worked well, without significant anomalies. However, the high demand for EO-1 imagery and the relative low priority of many of the sensorweb observations has reduced the number of achieved sensorweb images to 5-10 per week.
4. Goal: The SWB should enable scientists to track the spacecraft operations to view events and requests as they become spacecraft activities which then produce data, downlinked and processed. Design: All of the sensorweb modules were designed with database enabled tracking capabilities linked to the internet via web pages. Evaluation: Tracking pages have required significant background knowledge to interpret and thus have not been widely used by scientists. Efforts are underway to update the pages to make them more understandable.
5. Goal: The SWB should enable scientists to access a wide range of data associated with a science event, indexed by the science event not data source. Design: the SWB data access portal is designed to

link in the many data sources and enable access from a single point of entry. Evaluation: Implementation of the data portal is not yet complete thus evaluation is not yet possible.

4 Sensorweb Examples

4.1 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 overflights of each location on the globe per day (cover 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.

The active fire mapping algorithm [Justice et al. 2002] detects hotspots using MODIS thermal bands using absolute thresholds:

- T4>360K, 330K(night) or
- T4>330K, 315K(night)
  and T4-T11>25K, 10K (night)

It also uses a relative threshold algorithm which requires 6 nearby pixels in an up to 21x21 square that are cloud, smoke, water, and fire free. This triggers if the thermal reading is 3 standard deviations above the surrounding area.

- T4 > mean(T4)+ 3stddev(T4)
  and T4 - T11 > median(T4-T11)+ 3stddev(T4-T11)

Figure 5 shows the active fire map from October 2003 fires in Southern California. Figure 6 shows the context active fire map and a sensorweb trigger observation taken during this demonstration.

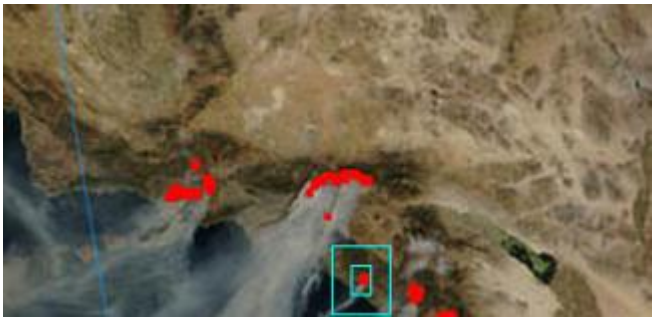

Figure 5: Active fire alerts for the recent October 2003 Southern California Fires. Red indicates active fires. The light blue box illustrates the background region used in the relative threshold detection.

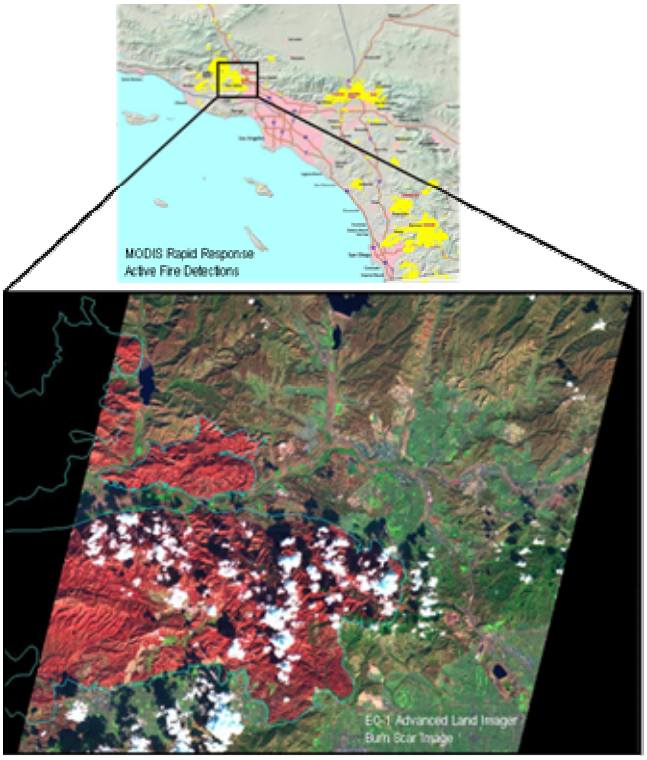

Figure 6: Sensorweb trigger images for October 2003 Southern California Fires. Above is the MODIS Active Fire Map display. Below is the EO-1 Hyperion image acquired via sensorweb trigger of the Simi/Val Verde fire area used in Burned Area Emergency Reclamation (BAER).

4.2 The Flood Sensorweb

The flood sensorweb uses the Dartmouth Flood Observatory Global Active Flood Archive to identify floods in remote locations automatically based on satellite data. The DFO flood archive generates flood alerts based on both MODIS and QuikSCAT [Nghiem 2001] satellite data. The flood sensorweb utilizes the DFO QuikSCAT atlas because it is not affected by cloud cover over flooded areas.

The DFO archive is produced by the DFO in collaboration with JPL/QuikSCAT team. In this process the QuikSCAT Scatterometer data is used to assess surface water conditions [Brakenridge et al. 2003, Nghiem et al. 1999]. Specifically the VV/HH ratio is used to assess surface water properties of the areas in 0.25 lat/lon degree bins. The 7 day running mean is used to dampen effects of short-duration rainfall over urban areas. These data are then compared to the seasonal (90 day) average of the previous year season to screen out seasonal wetlands. The screened alerts are then published to a DFO website. More recently MODIS and AMSR-E data has been incorporated into the triggering product.

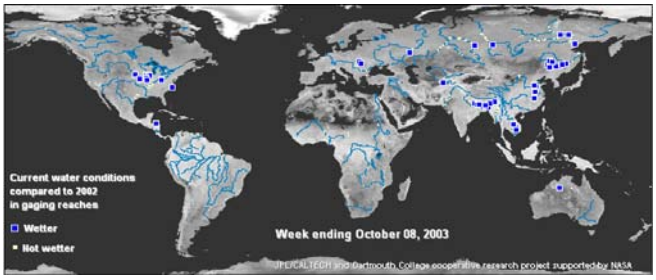

Figure 7: Dartmouth Flood Observatory Global Flood Alerts for October 2003.

In the flood sensorweb, active flooding alerts prime locations of known scientific interest 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 below.

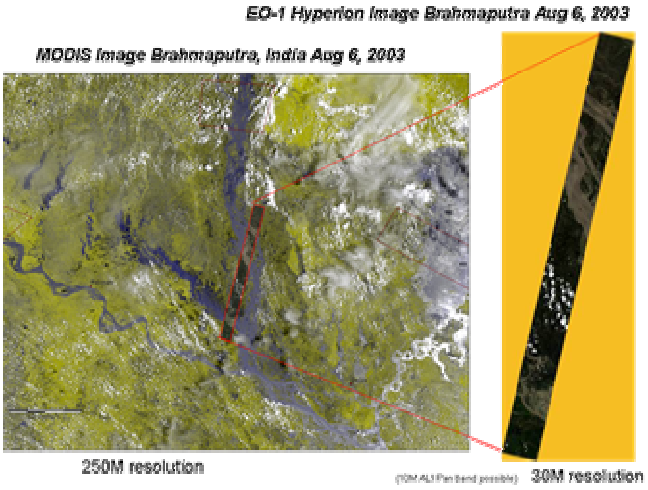

Figure 8: Examples of low-resolution MODIS imagery (left) and EO-1 imagery (right) from the Flood Sensorweb capturing Brahmaputra River flooding in India, August 2003.

4.3 The Volcano Sensorweb

In the volcano sensorweb, MODIS, GOES, 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 GOES [Harris et al. 2002] 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, are 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.

The MODIS alert system [Wright et al. 2002] has the advantage of high instrument sensitivity but has lower temporal resolution (MODIS generally has at least 4 overflights per day). MODVOLC deerives the normalized thermal index (NTI) from MODIS raw radiance values by computing (R22 – R32)/(R22+R32) where Ri indicates the use of the radiance value from MODIS band i. The NTI is compared to a threshold to indicate alerts and is generally available online within 3-6 hours of acquisition.

We have also linked into in-situ sensors to monitor volcanoes. We are working with a number of teams to integrate such sensors into our sensorweb. 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 cameras [Harris et al. 2003] to a number of volcanic sites worldwide (e.g., Kilauea, Hawaii; Erte Ale, Ethiopia; Sourfiere 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.

4.4 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. In collaboration with the Quikscat mission we are tracking snow and ice formation and melting and automatically triggering higher resolution imaging such as with EO-1.

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

5 Ongoing Extensions and Extra-terrestrial Applications

Terrestrial dust storms are of significant science interest and can be detected using several sensors including GOES, AVHRR, and MODIS [Miller 2003]. These storms can become quite large (100s of kms long) and are of interest because of dust transport and aviation impact. A dust storm sensorweb would utilize low resolution assets to track large-scale dust storms and autonomously direct high resolution assets such as EO-1 to acquire more detailed

data. Such data would improve scientific understanding of dust initiation and transport phenomena.

Figure 9 shows a large dust storm in the Persian Gulf as imaged by MODIS in November 2003. Dust storms can also be detected by ground-based instrumentation, such as operated by the U.S. Department of Agriculture in the U.S. Southwest and the Peoples Republic of China network of sites in the Gobi Desert. Detection and tracking of dust storms is also of considerable interest on Mars where such storms can grow to cover the entire planet.

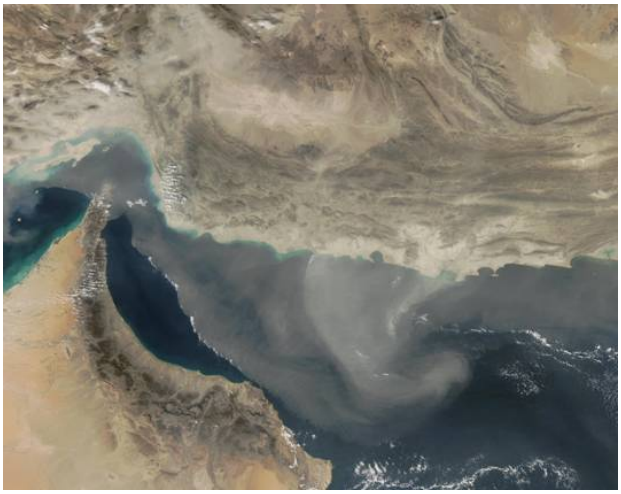

Figure 9: Dust Storm in Perian Gulf as captured by MODIS November 2003.

The sensorweb concept is directly applicable to deep space science applications, sun-earth connection science, and astrophysics applications [Davies et al. 2001]. For example, on Mars surface instruments could detect and/or track active, transient atmospheric and geologic processes such as dust storms. Alternatively, sun-pointed instruments could detect Coronal Mass Ejections (CMEs) and alert Earth orbiting magnetospheric instruments (e.g. IMAGE, MMC, MMS, …) to reconfigure to maximize science data.

6 Related Work & Summary

There has been considerable effort devoted towards closed loop science for rovers at ARC [Gulick et al. 2001], JPL [Castano et al. 2003], and CMU [Smith 2003]. These efforts have some similarity in that they have science, execution, and in some cases mission planning elements. However, because surface operations (e.g. rover) are very different from orbital operations, their focus is on integration with rover path planning and localization, reliable traverse, etc., whereas our efforts focus on reliable registration of remote sensed data, interaction with orbital mechanics, and multiple platforms. The MISUS system [Estlin et al. 1999] also describes a closed loop multi-rover autonomous science architecture.

One closely related effort is led by Keith Golden [Golden et al. 2003] at NASA Ames to enable real-time processing of Earth Science data such as weather data. However, this work focuses on the data processing and information gathering aspect of the problem, and thus is complementary to our sensorweb work which focuses on the operations aspect of the problem. Indeed, we have discussed with Golden the possibility of a joint sensorweb information gathering demonstration.

The Autonomous Sciencecraft Experiment on EO-1 [Chien et al. 2003] demonstrates an integrated autonomous mission using onboard science analysis, replanning, and robust execution. The ASE performs intelligent science data selection and autonomous retargeting. ASE represents a single spacecraft onboard autonomous capability. In contrast the sensorweb uses multiple assets in concert.

This paper has described ongoing work to link together 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.

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