Linking Satellites Via Earth "Hot Spots" and the Internet to Form Ad Hoc Constellations

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ABSTRACT

As more assets are placed in orbit, opportunities emerge to combine various sets of satellites in temporary constellations to perform collaborative image collections. Often, new operations concepts for a satellite or set of satellites emerge after launch. To the degree with which new space assets can be inexpensively and rapidly integrated into temporary or "ad hoc" constellations, will determine whether these new ideas will be implemented or not. On the Earth Observing 1 (EO-1) satellite, a New Millennium Program mission, a number of experiments were conducted and are being conducted to demonstrate various aspects of an architecture that, when taken as a whole, will enable progressive mission autonomy. In particular, the target architecture will use adaptive ground antenna arrays to form, as close as possible, the equivalent of wireless access points for low earth orbiting satellites. Coupled with various ground and flight software and the Internet, the architecture enables progressive mission autonomy. Thus, new collaborative sensing techniques can be implemented post-launch. This paper will outline the overall operations concept and highlight details of both the research effort being conducted in the area of adaptive antenna arrays and some of the related successful autonomy software that has been implemented using EO-1 and other operational satellites.

Keywords: smart antennas, adaptive antenna arrays, sensor webs, ad hoc constellations, mission autonomy and collaborative remote sensing

1. INTRODUCTION

The Earth Observing 1 (EO-1)[1] spacecraft has been used and continues to be used as the core satellite to demonstrate various integrated autonomy technology experiments. The original mission of EO-1 was to validate a number of space technologies during its first year. After successful completion of the first year objectives, the mission evolved into an on-orbit testbed for sensor web concepts. Connectivity between satellites and ground sensors has been implemented through various "makeshift" efforts to demonstrate the utility of these configurations. In parallel, the Earth Science Technology Office (ESTO) awarded a grant to perform research on next generation antenna technology in S and X-bands, also laying the ground work for Ka-Band, to create as close to total coverage as possible for low earth orbiting satellites. In this way, low earth orbiting satellites could have continuous Internet connectivity and thereby enable more science yield from available on orbit instrument resources by managing those resources more wisely. For example, of the 19,000 plus images taken thus far on the EO-1 mission, approximately two thirds are cloudy. Since one of the main instruments on EO-1 is the Hyperion, a hyperspectral instrument, clouds are not desired. Experiments conducted with EO-1 used the GOES satellite and other satellite observations of clouds to make real time decisions on which images to acquire. Increasing the "cloud-free" image yield by just 10-20% would result in significant savings for the mission.

Interestingly, by connecting hourly GOES observations to task planning for EO-1, in effect, connects GOES and EO-1 as a temporary or "ad hoc" constellation for negligible cost. More details on this particular experiment will be provided later in this paper.

But the key to making this concept highly desirable is the antenna connectivity for these satellites. Presently, most of the NASA low earth orbiting satellites such as EO-1, and in particular polar orbiting satellites, communicate through the Ground Network (GN) ground stations, which consist mostly of 11 meter antennas. These antennas are expensive, roughly costing $2 - 4 million each and costly to operate. The main ground stations are in Alaska, Norway and Antarctica to maximize how often these satellites can be viewed and to minimize how many ground stations are needed. EO-1, for example, uses about 6 – 8 downlink passes per day with a length of 8 – 10 minutes each. EO-1 contains a 48 Gbit science recorder, collecting between 13 – 48 Gbps of data between downlink passes. During the passes, EO-1 downlinks the recorder data at 105 Mbps. But some new missions are specifying the collection of as much as 10 times more data. Thus, with the limited data pipes for each orbit, future missions are limited. Furthermore, because of the limited number of ground stations, use of these ground contacts to manage and coordinate in-orbit operations of EO-1 and other satellites, are limited. EO-1 can use the Tracking and Data Relay Satellite System (TDRSS) for almost continuous coverage, however, there is no interoperability between EO-1 to other satellites via TDRSS.

If the antennas were inexpensive and relatively maintenance free, then numerous antennas could be placed around the globe cost-effectively, thus providing much more coverage (if not total coverage). Furthermore, as larger amounts of data are required to be downlinked, many lower bandwidth downlink pipes could be substituted thus providing more cost effective space to ground links for large volumes of data. Finally, by connecting these less expensive antennas to the Internet and using protocol standards such as Internet Protocol (IP) and other higher level messaging protocol,l such as GSFC Mission Systems Evolution Center (GMSEC)[7] protocols, seamless satellite interoperability can be achieved.

Figure 1 depicts the set of related sensor web tasks that attempt to take steps towards this vision as depicted in figure 2, using EO-1 as the central hub for these experiments.

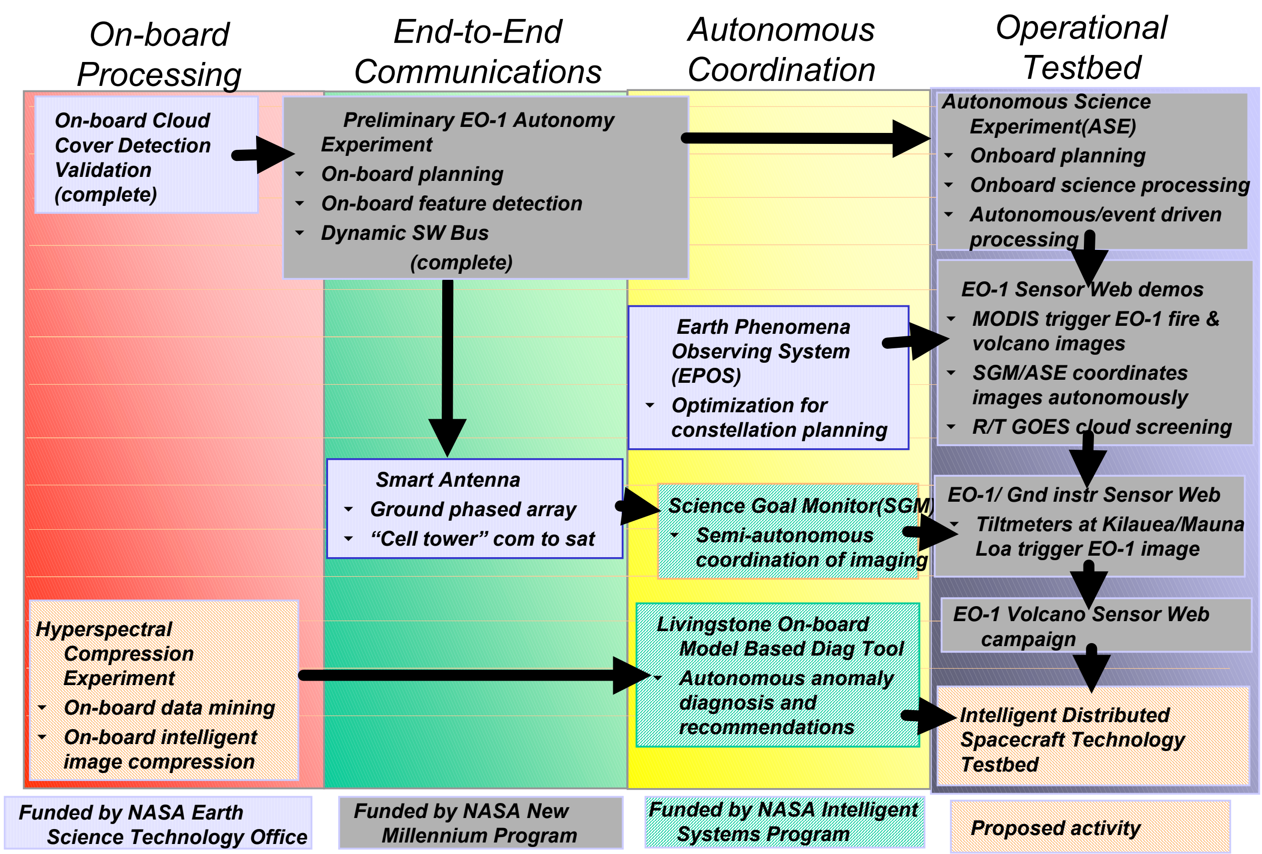

Figure 1 Funded sensor web related experiments using EO-1 as the platform

2. OPERATIONAL CONCEPT

The general operations concept is to extend Internet capabilities to low earth orbiting satellites and to make the space-ground interface as seamless and interoperable as possible. Figure 2 depicts how the architecture would look with the addition of antennas that act as wireless access points for various satellites and other vehicles such as airplanes. Note that in addition to providing continuous connectivity, standards are needed to allow messages to pass seamlessly between software entities in the spacecraft and on the ground. Furthermore, for the long term vision, software could be uploaded and immediately plugged in and operate similar to JAVA applets.

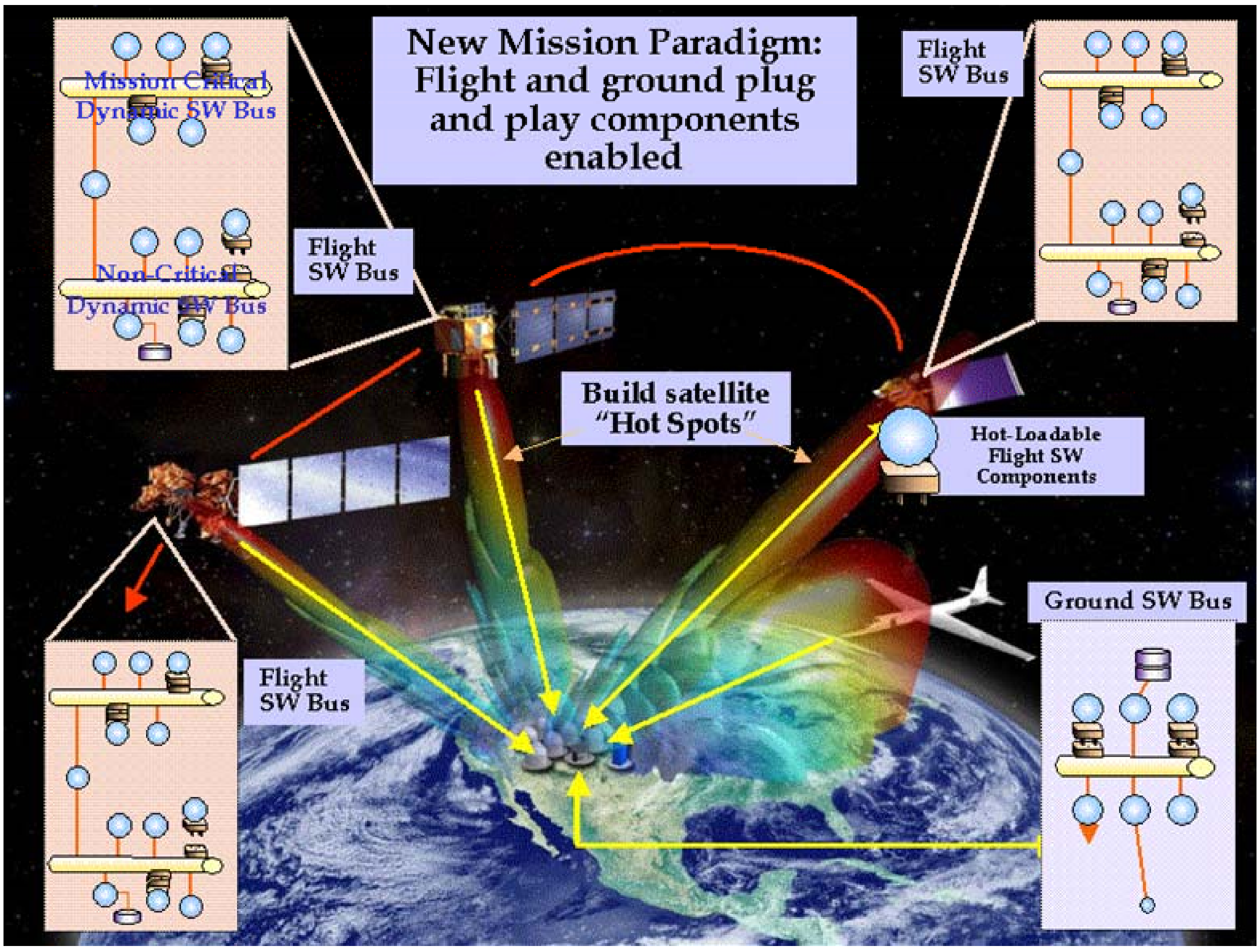

Figure 2 Architecture concept for use of smart antennas to build satellite "hot spots" thus enabling Internet type of connectivity to low earth orbiting satellites. Ultimately, this would enable interoperability and progressive mission autonomy.

Note that this architecture would allow the proposed space architecture to evolve more rapidly. The traditional approach for building missions involves large-scale system engineering and corresponding costs. In this architecture, many small incremental improvements can be achieved without large expenditures. This has been demonstrated over the last three years as the EO-1 sensor web has evolved. Figure 3 depicts part of the connections and triggers established to enable collaborative imaging. One example was having the MODIS instrument on Terra and Aqua detect hot pixels and then, via the Rapid Fire workstation in the MODIS instrument center, send a trigger to task the EO-1 spacecraft to acquire a high resolution image via its Hyperion instrument.

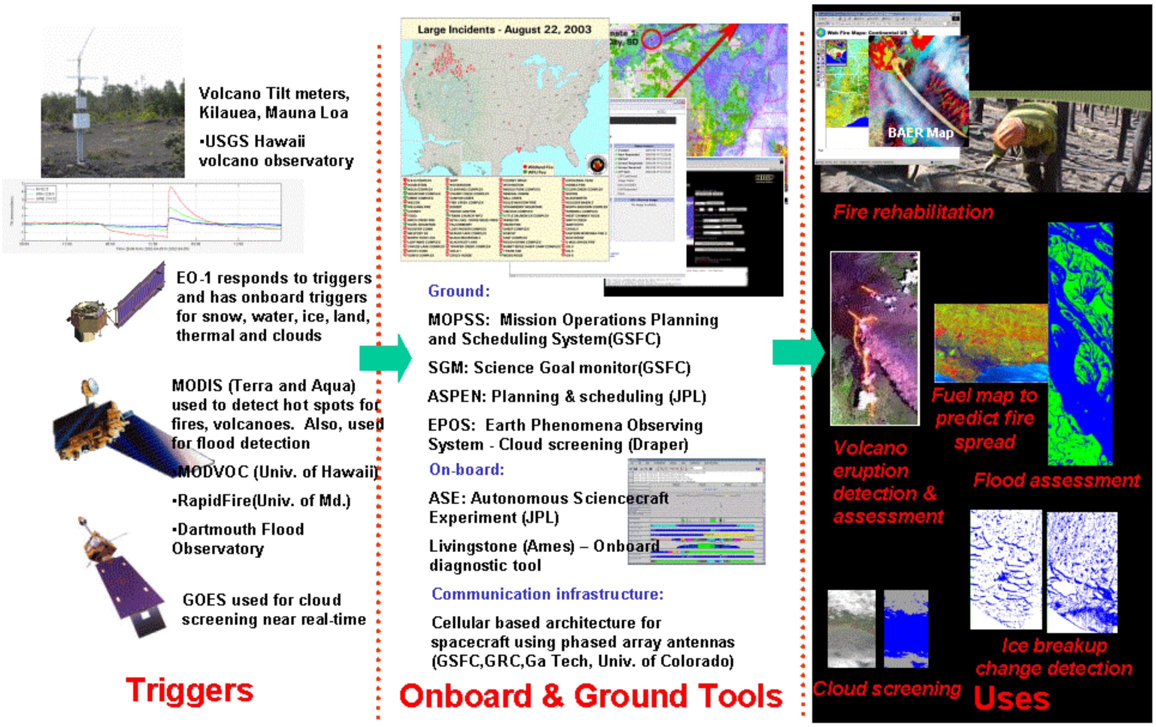

Figure 3 Pictorial representation of some of the sensor web related experiments conducted thus far and also to be conducted.

3. SMART ANTENNA RESEARCH

The vision for our antenna system research[2] is to find the next generation antenna technology that would eliminate or minimize moving parts. Using the emerging technology of digital signal processing, software is used to shape the antenna pattern. In essence, if taken to the end goal, the software would shape the antenna pattern to follow the target satellite without moving parts such as the large motors used to slew the 11 meter dishes at the GN ground stations. Furthermore, the software is also able to shape the antenna pattern to optimize the desired signal and minimize the impact of interference. Thus, whereas most antenna systems can have self interference because of the signal bouncing off buildings and other structures, called multipath, smart antenna technology can be used to actually enhance the desired signal thus leveraging the multipath. Therefore this technology can be used to create wireless access points for low earth orbiting satellites especially, if in the future, medium to large constellations are launched. This technology will provide a more cost effective means for a ground station to handle multiple satellites simultaneously. NASA's GN ground stations can typically handle only one satellite per ground station and thus act as bottleneck for potential future constellations.

Our research effort is a collaborative effort between NASA GSFC, NASA Glenn Research Center (GRC), Georgia Institute of Technology and University of Colorado. GSFC provides operational and systems expertise, GRC and the University of Colorado provide microstrip patch antenna expertise and the Georgia Institute of Technology provides the adaptive array algorithm expertise and system integration expertise. The research is scheduled as a three year effort and has evolved since the inception of the task which began April 2003. The future plan along with those already accomplished are as follows:

a. Demonstrate a 4 element ground adaptive array in S-band (data rate was 2 kbps) that is able to capture data from EO-1 with no steering. This was successfully completed in April 2004. Figure 4 is a picture of the test setup. Note that the front end elements were comprised of very cheap components such as PVC pipe and wire.

Figure 4 Test set up at Georgia Tech for the S-band test showing the 4 element adaptive array used with EO-1

b. Demonstrate by April 2005 a 2 – 4 element adaptive array in X-band (data rate 6 Mbps) using the SAC-C with mechanical steering. Figure 5 represents some of the options being considered for the experiment. We are constrained by cost and are trying to make this demonstration system as inexpensive as possible. At present, the cost ranges for the projected system are estimated between $5K - $20K per element. In addition, to create a fully functional system would require the digital processing equipment behind the elements and such devices as bit-syncs and Reed Solomon decoders. But, initial cost estimates bode well for the target being very cost effective once it reaches production stage.

c. Demonstrate a 2 – 4 element adaptive array in X-band (data rate 6 Mbps) using SAC-C with electronic steering. Figure 6 and 7 depict two technologies that GRC are developing for use as elements in the adaptive array. Figure 6 shows a reflectarray which is an electronically steerable antenna consisting of thin film ferroelectric phase shifters and a quasi-optical feed. Figure 7 shows a Space Fed Lens which consists of a focal surface and a planar lens array. Both the surface and the array are realized using microstrip patch antennas and arranged in two layers of patch antennas and a beamforming manifold to focus the energy of the multilayer circuit board. The size of the elements being considered range from 10 cm to 100 cm in diameter. Figure 8 is an artistic conception of the how the array would look if configured with space fed lens shown to scale on a tennis court for reference.

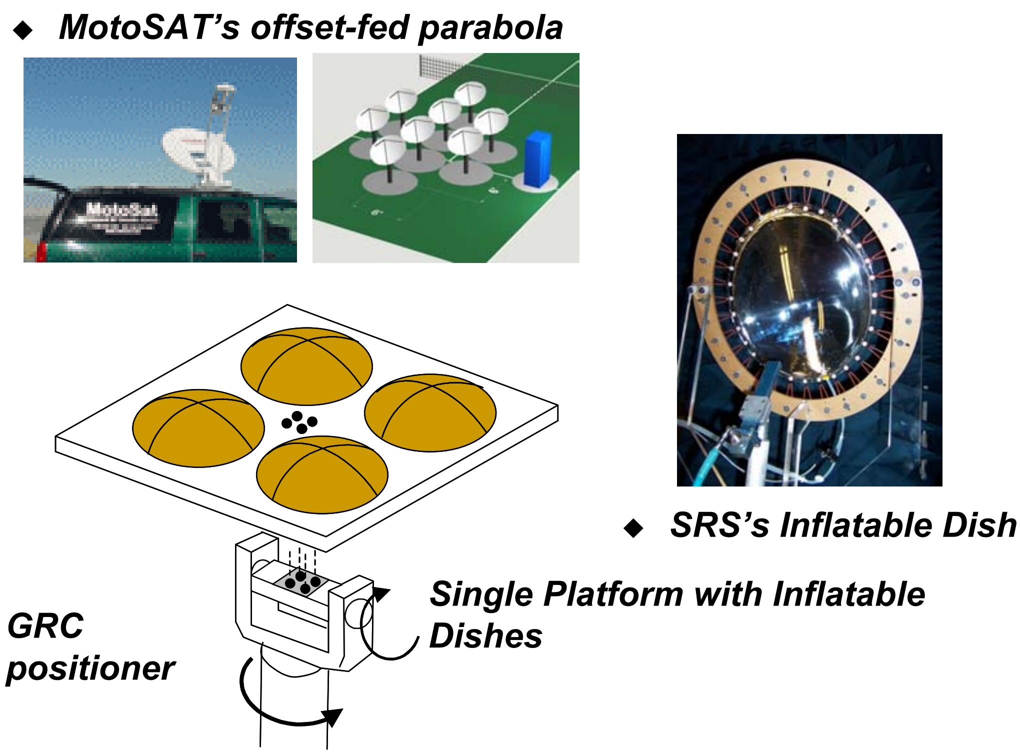

Figure 5 Depicts two of the options being considered to build a 2 – 4 element X-band adaptive array with mechanical steering for use with the SAC-C spacecraft.

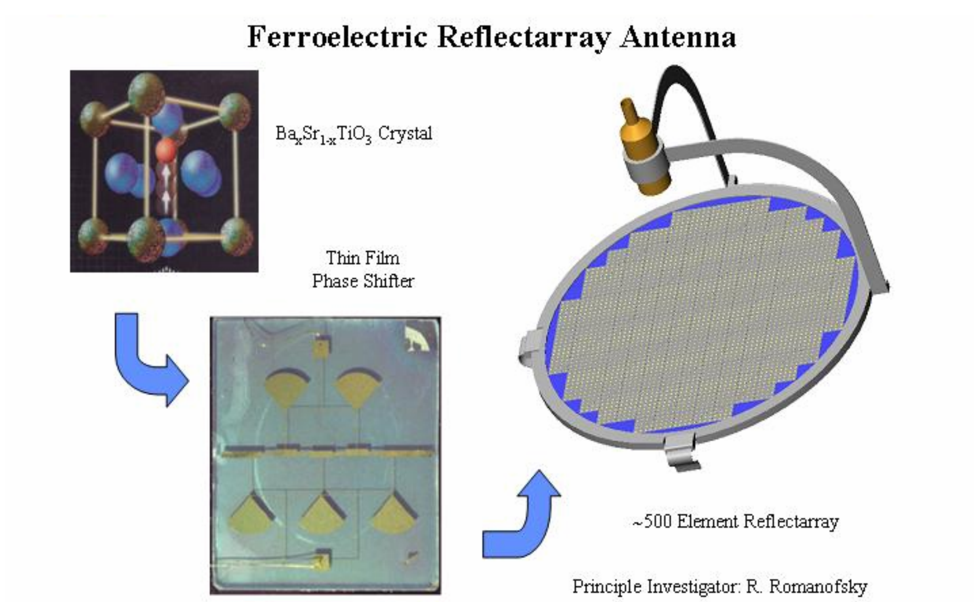

Figure 6 Reflectarray being developed by NASA Glenn Research Center

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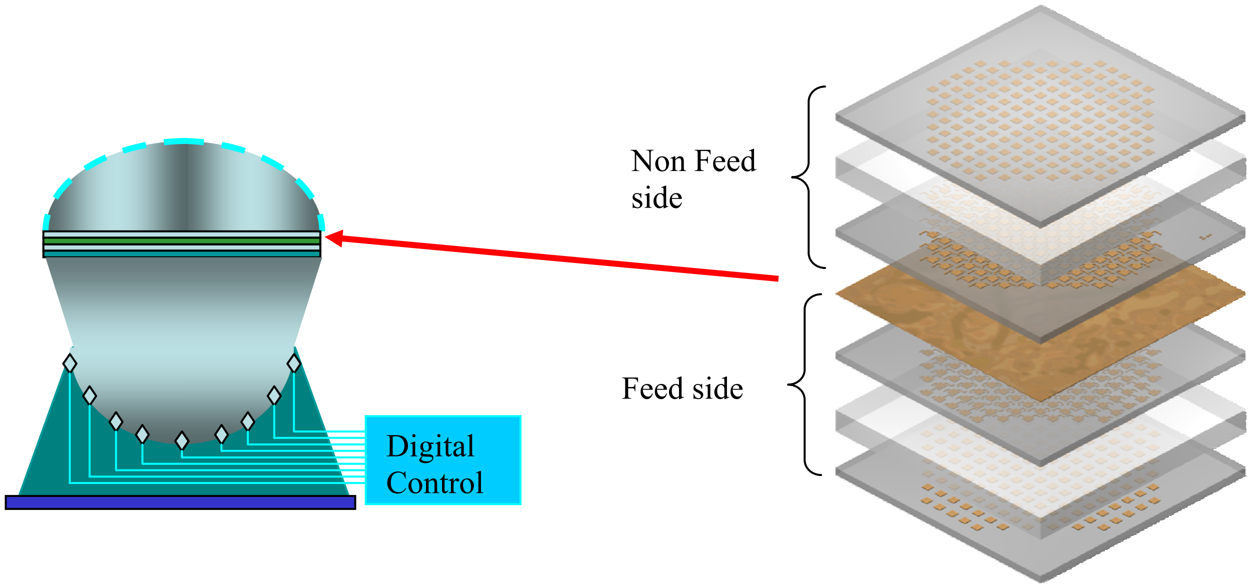

Figure 7. Space fed lens being developed by NASA Glen Research Center.

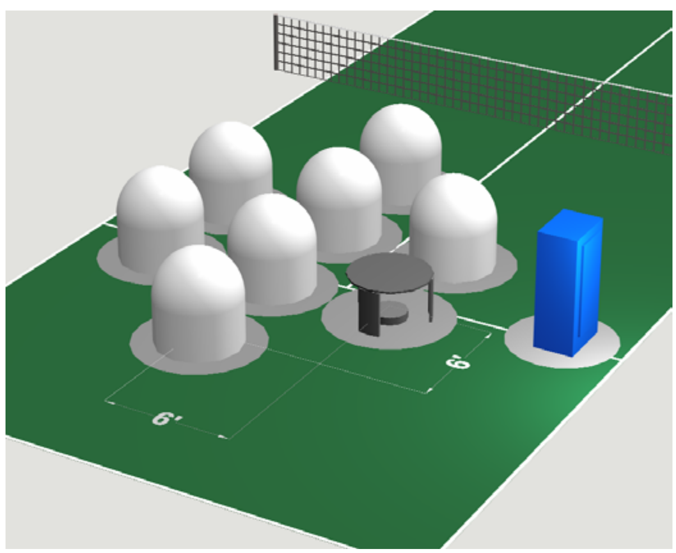

Figure 8 Array of electronically steered space fed lens. The outputs of each space fed lens is adaptively combined. The antenna elements are superimposed on a tennis court to show the relative scale of the elements.

4. AD HOC CONSTELLATION AND SENSOR WEB SCENARIOS

Over the past 3 years a number of scenarios have been executed using a variety of satellites. EO-1 has been the key satellite since that is the satellite that we control. The first time that EO-1 actions were automatically triggered by other satellites was in August 2003. At that time, we used the data that Terra and Aqua generate in near real-time via the Rapid Fire workstation in the MODIS instrument center. The Rapid Fire workstation generates hot pixel alerts. Each of the pixels is a 1 km square. During that summer, there were a number of large wild fires which were tracked by the Forestry service. Once a fire was identified, MODIS was used to locate hot pixels which determined where the selected fire was burning at present. The Science Goal Monitor (SGM)[3] which is located in the EO-1 MOC, along with the other planning components automatically generated tasking commands for the EO-1 spacecraft to acquire a high resolution image with its Advance Land Imager, another of the EO-1 instruments. Once the image was taken, the image was transferred to the USGS EROS Data Center for level 0 and level 1 processing. Next the image went to the University of Maryland for synchronizing the image with a map. The image was then transferred to the Forestry Service which used the image to create Burn Area Reflectance Classification (BARC) maps such as the one depicted in figure 9.

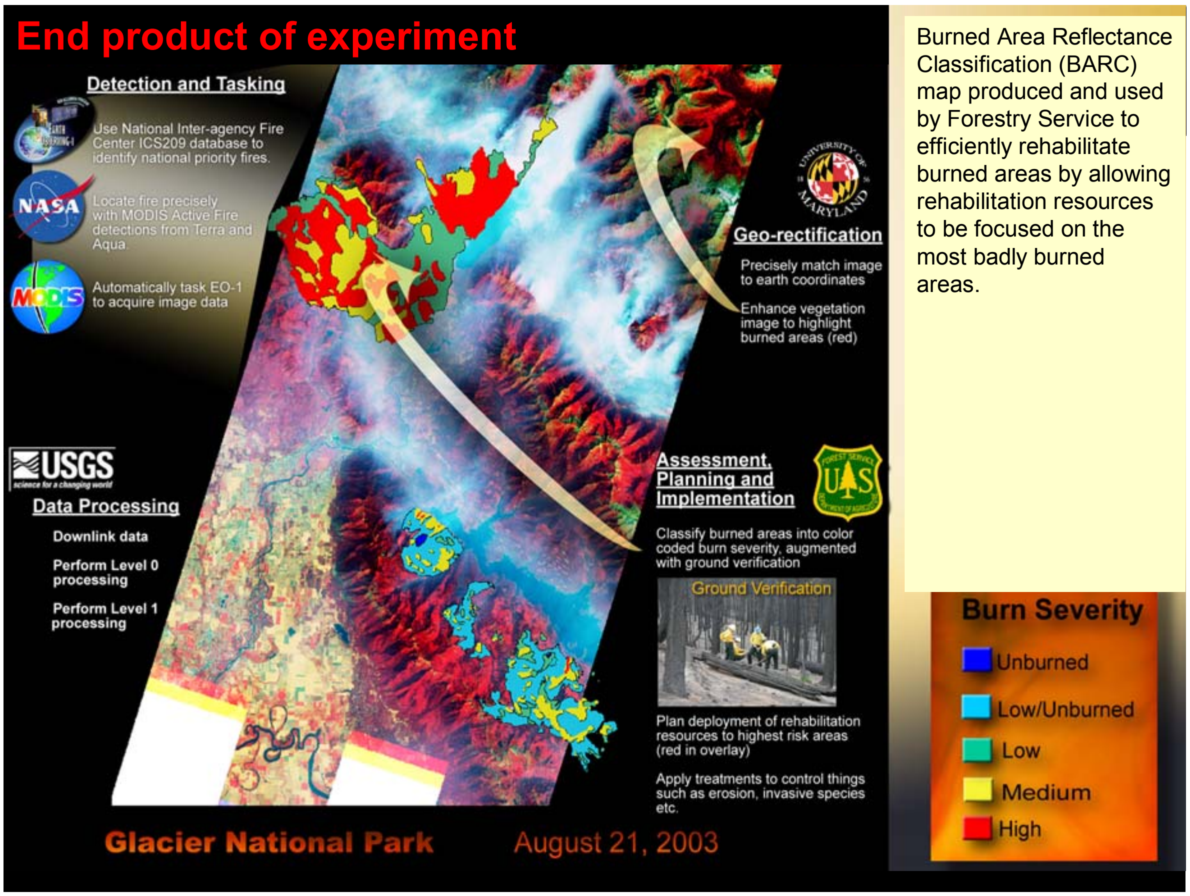

Figure 9 BARC map created and used by the Forestry Service as a result of the EO-1 fire sensor web experiment. This BARC map was supplied by Rob Sohlberg from the University of Maryland in conjunction with the Forestry Service

It turned out that the Forestry Service required a 24 –48 hour turn-around for receiving these processed images from the time of the tasking request, in order to create the BARC maps in sufficient time to help the Burned Area Emergency Rehabilitation team. This turn-around time was faster than previously available. The demonstration was performed without any of the new antenna technology, however, once the proof of concept was complete through available communication components and the Internet, the turn around time for this scenario will improve as new autonomy technology and communications technology are deployed.

Other similar scenarios have been deployed using the MODIS instrument to both detect and then acquire high resolution images through a similar automated ground sequence. In fact, at present, EO-1 is conducting a 500 image volcano campaign which is a combination of triggers from the University of Hawaii's MODVOLC website which processes MODIS data and a tilt meter ground instrument trigger at the USGS Hawaiian Volcano Observatory. Furthermore, the Autonomous Sciencecraft Experiment (ASE)[4] has been demonstrating onboard thermal classification to detect volcanoes and autonomously retask EO-1 to re-image a detected volcano. The following is a list of the onboard classifiers included with ASE software on EO-1 (including the thermal classifier):

- Thermal anomaly detection – uses infrared spectra peaks to detect lava flows and other volcanic activity.
- Cloud detection [5] – uses intensities at six different spectra and thresholds to identify likely clouds in scenes.
- Flood scene classification – uses ratios at several spectra to identify signatures of water inundation as well as vegetation changes caused by flooding.
- 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.
- Generalized Feature detection – uses trainable recognizers to detect such features as sand dunes and wind streaks (to be flown)[6]

Another scenario used, linked EO-1 actions to the GOES satellite cloud top pressure website. The website updates the data for cloud cover over the continental U.S. every hour. A plan was uplinked to EO-1 to take one of multiple conflicting image targets. The conflict arose because they are along one orbit and EO-1 cannot slew fast enough to image all of them. One to four hours before passing over the set of targets, the GOES website is polled and the target areas are checked for cloud cover. The least cloudy of the targets is selected. A command is sent to EO-1 in real-time to direct EO-1 to image the selected the target, thus allowing a more efficient use of mission resources to get a higher yield of cloud free images. This is particularly useful for transient images, such as fires, for which there are limited opportunities to acquire images.

5. SOME GOALS FOR SENSOR WEBS AND AD HOC CONSTELLATIONS

The ultimate goal for ad hoc constellations and sensor webs is to respond quickly to transient events and to be able to rapidly reconfigure available assets for science goals. The responsiveness of the end-to-end architecture is limited by the flexibility and speed of communications. Just as the Internet changes in nature with upgrades in performance, so will sensor webs and ad hoc constellation change as performance increases. At first, we can only have responses end-to-end in the range of hours to a couple of days. Ultimately, when the speed of communications gets faster and there are more flexible assets, then the response time will decrease to minutes thus enabling newer capability. For example, our present sensor web can support wildfire rehabilitation efforts because only responses in days are needed. When sensor webs are fast enough, perhaps real-time wild fire management assistance will be enabled.

Another key goal is to be able to put together data from multiple satellite sources into a composite picture. In figure 9, the Forestry Service did just that from the fires in California during November 2003 which were the largest wildfires in state history. By being able to fuse multiple satellite and airplane sources, they were able to be more responsive to rehabilitating fire damage.

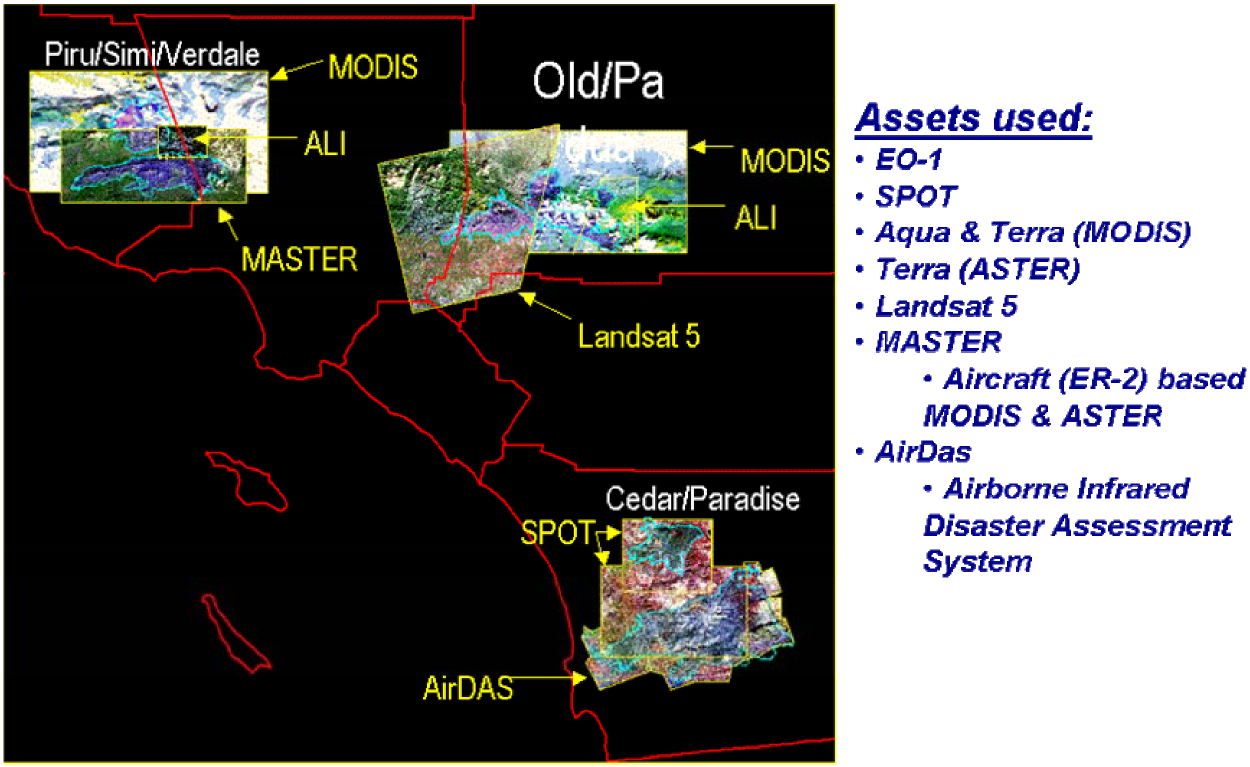

Figure 10 Example of data fusion for the California fires in November 2003 using multiple space and airborne assets

6. CONCLUSION

As EO-1 continues to experiment with various sensor web/ad hoc constellations, our team strives to be a catalyst for future high performance ad hoc constellations of the future. The key lies in cost effective end-to-end, flexible mission communication architectures, which in turn depend on next generation antenna systems. If we can approach total coverage for low earth orbiting satellites from the ground along with the development of inter-satellite communications, then there will be an explosion of sensor web/ad hoc constellation applications.

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 Daniel Tran, Gregg Rabideau, Rebecca Castano, Ben Cichy, Nghia Tang, Michael Burl of JPL, Seth Shulman, Stephen Ungar and Thomas Brakke of GSFC, Lawrence Ong of SAIC, Jerry Hengemihle and Bruce Trout of Microtel LLC, Jeff D'Agostino of the Hammers Corp., Robert Bote of Honeywell Corp., Jim Van Gaasbeck and Darrell Boyer of ICS, Michael Griffin and Hsiao-hua Burke of MIT Lincoln Labs, Ronald Greeley, Thomas Doggett, and Kevin Williams of the Arizona State University, Victor Baker and James Dohm of the University of Arizona, and Rob Sohlberg of the University of Maryland, and Anarahda Koratkar of University of Maryland at Baltimore County.

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