Virtual Mission Operations of Remote Sensors with Rapid Access to/from Space

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This paper describes network-centric operations, where a virtual mission operations center autonomously receives sensor triggers, and schedules space and ground assets using Internet-based technologies and service-oriented architectures. For proof-of-concept purposes, sensor triggers are received from the United States Geological Survey (USGS) to determine targets for space-based sensors. The Surrey Satellite Technology Limited (SSTL) Disaster Monitoring Constellation satellite, the UK-DMC, is used as the space-based sensor. The UK-DMC's availability is determined via machine-to-machine communications using SSTL's mission planning system. Access to/from the UK-DMC for tasking and sensor data is via SSTL's and Universal Space Network's (USN) ground assets. The availability and scheduling of USN's assets can also be performed autonomously via machine-to-machine communications. All communication, both on the ground and between ground and space, uses open Internet standards.

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I. Introduction

One of NASA's strategic objectives is to develop new space-based and related capabilities for advancement of the study of the Earth's climate and ecological systems from space. In particular, the work described in this paper advances Earth observation from space via time-critical sensor control, improves scientific understanding via distributed sensor web interactions and data mining techniques, and demonstrates new technologies with the potential to improve future operational systems.

In support of NASA's Earth Science Technology Office (ESTO) Advanced Information Systems Technology (AIST) programs, NASA Glenn Research Center (GRC) developed information delivery protocols, and secure, autonomous, machine-to-machine communication and control technologies to enable integration of distributed Earth system sensors and processing components into sensor webs. GRC's research efforts concentrated on the architecture and development of system building blocks leading to autonomous sensor webs. GRC leveraged its relationships with Cisco Systems, General Dynamics, Universal Space Network (USN), the Army and Air Force Battle Labs, and Surrey Satellite Technology Limited (SSTL) to develop a ground and space-based network and relevant protocols to demonstrate time-critical interoperability between integrated, intelligent sensor webs consisting of space-based, fixed, and mobile terrestrial-based assets.

GRC developed the necessary infrastructure and protocols to enable near real-time commanding and access to space-based assets. Protocol development culminated with a space-flight demonstration of large file transfers distributed across multiple satellite ground stations.

GRC worked with General Dynamics, Surrey Satellite Technology Limited, and USN to integrate General Dynamics' Virtual Mission Operation Center (VMOC) technology and open architecture interfaces with selected terrestrial and space-based sensor webs able to demonstrate time-critical interoperability and intelligent integration. This paper concentrates on the use of the VMOC to autonomously schedule and obtain services from multiple independent parties in order to task a space-based sensor and obtain sensor data in the shortest time.

This research also fulfilled NASA's goal to promote commercial participation in exploration to further U.S. scientific, security, and economic interests and to involve the U.S. private sector in the design and development of space systems. GRC utilized U.S. and, when necessary, foreign commercial space capabilities and services to accomplish this. The commercial companies participating in this research effort include:

- General Dynamics – Virtual Mission Operations Center technology
- Universal Space Network (USN) – ground station development and ground station network
- Surrey Satellite Technology Limited (SSTL), a United Kingdom company – commercial imagery satellite

II. Secure, Autonomous, Integrated Space/Ground Sensor webs

A. Concept of Operations (CONOPS)

The overall goal of the secure autonomous integrated space/ground sensor web was to demonstrate secure network centric operations of space/ground assets owned and operated by multiple parties. In order to accomplish this, a network consisting of terrestrial sensors (seismic sensors), a virtual mission operations center (VMOC), multiple ground stations and a spacecraft were used with the flow of information shown in Figure 1. A seismic sensor update was received by the VMOC that indicated some exceptional event of interest. The VMOC then decided what other sensors or sensor network could be brought to bear in order to gain more information on that event. In this situation, the terrestrial sensor web is the Global Seismic Network[1] with the trigger information obtained from the United States Geological Survey (USGS). A limited demonstration, Phase I, of the overall concept occurred in July 2009 (see section III, Automated Service Agreements).

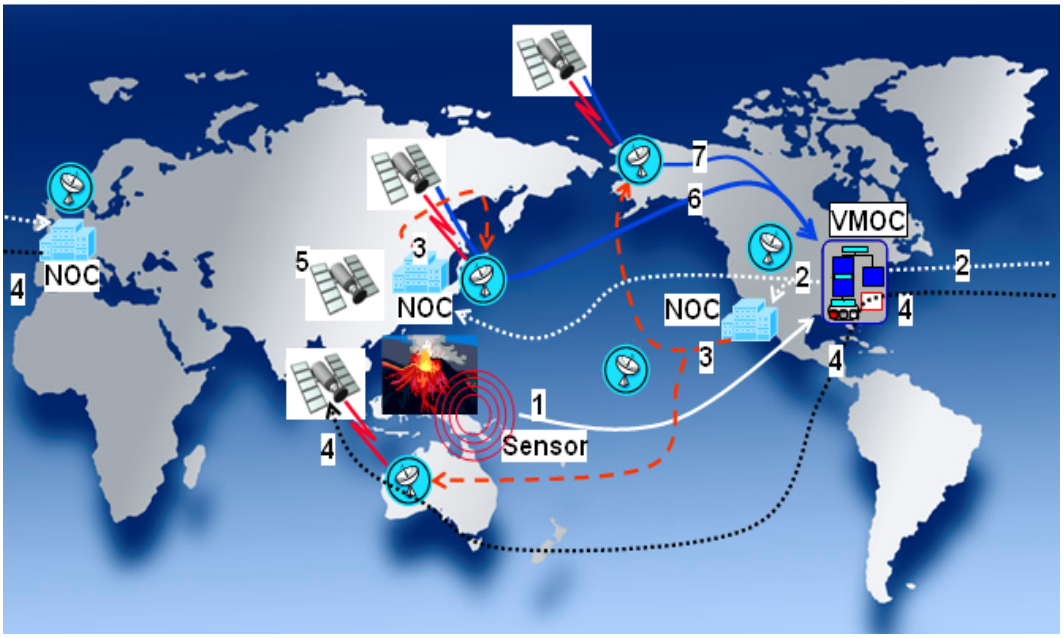


Figure 1: Secure, Autonomous, Integrated Space/Ground Sensor Web

Figure 1 illustrates the overall concept of operations (CONOPS) as a series of events labeled 1 through 7.

1) The VMOC receives a trigger of a seismic event from the USGS notification system. The trigger level can be set to some threshold. That trigger sets the autonomous sensor web into motion.
2) The VMOC's job is to task other sensors and reserve and/or configure whatever infrastructure is necessary to obtain the requested data. In this instance, the other sensor is SSTL's United Kingdom Disaster Monitoring Constellation (UK-DMC) satellite. The supporting infrastructure includes Internet-enabled ground stations: one in Guildford, England owned and operated by SSTL, and three ground stations in North Pole, Alaska, South Point, Hawaii and Mingeneu, Australia, owned and operated by USN.
3) Once the VMOC coordinates all facilities for availability and requests reservation of those assets, the individual entities cooperate to configure and operate their facilities and infrastructure, rather than the VMOC assuming complete system control. This is accomplished by machine-to-machine communication and negotiation. For example, USN may get a request to take a pass of the UK-DMC satellite over its Australian ground station at a given date and time. USN will accommodate the request, set up USN's infrastructure and ensure the data paths are in place to enable data to get back to the VMOC. Likewise, SSTL schedules the UK-DMC to turn on and begin transmitting over the ground station in Australia.
4) The commands are sent to the spacecraft regarding when to capture sensor data and when to transmit that data to the ground. Those commands are currently passed to the satellite via SSTL's 'home' ground station; however, they could conceivably be passed to the satellite via a third-party ground station such as one of the other international DMC ground stations, or USN's Australian site as illustrated in Figure 1.
5) The image is taken over the area of interest corresponding to the seismic event.
6) The image is then downloaded. As illustrated, this image is downloaded to a third party ground station in Japan.
7) If an image is too large to be transmitted in its entirety during a single pass, the remaining portion of the file can be transmitted via a second ground terminal. In Figure 1, the second ground station is in Alaska. A limited demonstration of large-file transfer over multiple ground stations was successfully performed using this network in September and October 2009[2].

B. Space Infrastructure

The spacecraft used for all networking experiments is United Kingdom Disaster Monitoring Constellation (UK-DMC) satellite. The UK-DMC satellite is one of seven on-orbit Internet-enabled imaging satellites, of which six are currently operational, including the later UK-DMC-2 satellite (so the UK-DMC is now also known as UK-DMC-1). Two more DMC satellites are expected to join the constellation with launch in 2010. The DMCs are operational satellites, providing imagery both under the International Charter for Space and Major Disasters (the "Disasters Charter") and as part of a commercial, money-making venture selling imagery (DMC International Imaging Ltd). Individuals can request an image of an area of the Earth (and may need to pay). These satellites are in a sun-synchronous polar orbit with an altitude of 680km and a period of approximately one revolution every 100 minutes. A reasonably usable pass will have the satellite in view of any one ground station for 8 to 14 minutes. Disruption occurs when the satellite cannot communicate with a ground station. The round-trip-time delay from ground station to the spacecraft is under ten milliseconds, thus propagation delay is not the issue here (unlike for deep space).

The UK-DMC-1 satellite carries three solid-state data recorders (SSDRs): one with a StrongARM Processor and two using the Motorola MPC8260 PowerPC processor. For our tests we use one of the MPC8260 SSDRs. The SSDR has a RTEMS (Real-Time Executive for Multiprocessor Systems) operating system including POSIX (Portable Operating System Interface for Unix) API (application program interface). The storage capacity on the PowerPC SSDRs consists of 1 or 0.5 Gbyte of RAM while the bootable operating system image is limited to 0.5 Mbytes.

The communication systems consist of a slow 9600 bits-per-second (bps) uplink for commanding and the much faster 8.134 Mbps downlink for transmitting high-resolution imagery. The data link is commercial off-the-shelf standard Frame Relay/HDLC (High-Level Data Link Control). The UK-DMC-1 satellite uses Internet Protocol (IP) packets to move data to and from the satellite. The network protocol is IPv4 but could easily be changed to IPv6. The DMC satellites have uplink/downlink asymmetries of up to 850:1 for S-Band transmitters and 8333:1 for X-Band transmitters on later DMC satellites, leading to an unusual network environment which many protocols are unable to cope with efficiently, e.g. TCP acknowledgement would congest the uplink, while TCP segments would be unable to fill the downlink to capacity due to TCP's backoff algorithms. Higher link asymmetries are planned for future DMC satellites, which will have faster downlinks for higher-resolution imagery. The file transport protocol used is *Saratoga*,[3] a simple, high-rate, rate-based, negative-acknowledgement UDP/IP-based file transfer protocol that can operate over extremely asymmetric links and tolerate loss. *Saratoga* is specified in a public internet-draft.

The UK-DMC-1 satellite is the only DMC satellite to have an onboard experimental networking payload, the Cisco router in Low Earth Orbit (CLEO). From 2004 through 2008, CLEO was used for the advanced IP network testing and demonstrations.[4] The UK-DMC-1 satellite was the first satellite to source IPv6 traffic and the first to demonstrate IP security protocols[5,6,7] Because of these successful tests, SSTL allowed the UK-DMC-1 to be used for large-file transfer demonstrations over multiple ground stations. For large-file transfer tests, the Delay Tolerant Networking (DTN) Bundle Protocol[8] was used with DTN-conformant bundles constructed directly in the SSDR[9].

C. Ground Infrastructure

The ground infrastructure, shown in Figure 2, consists of a number of ground stations scattered throughout the Earth and a VMOC located at NASA's Glenn Research Center in Cleveland, Ohio. Each ground station router has a serial link to the RF system, a LAN Ethernet connection to a workstation that is used to upload and download files, and a WAN Ethernet link that eventually leads to the open Internet. An additional workstation (Bundle Agent) has been placed on the LAN Ethernet link to perform store-and-forward operations using the experimental store-and-forward Bundle Protocol, which was developed by the Internet Research Task Force (IRTF) DTN Research Group. Here, store-and-forward technology is used to break transport protocol control loops and handle rate mismatch problems between the Space-Ground link and the terrestrial link between ground stations and data combining location. In this case, the data combining location is a DTN bundle agent co-located with the VMOC. The ground station, network architecture and details for the UK-DMC-1 onboard system are described in "Secure, Network-Centric Operations of a Space-Based Asset: Cisco Router in Low-Earth Orbit (CLEO) and Virtual Mission Operations Center (VMOC) ".[4]

1. SSTL Ground Station

SSTL's ground station is located in Guildford, England. SSTL's ground station is a stable operational system. Therefore, this ground station is used to execute each new test prior to attempting to duplicate the test on any other station,to allow separation of debugging the tests and debugging newer groundstations.

2. Universal Space Network

NASA GRC and Universal Space Network (USN) entered into a contract for USN to provide three ground stations configured to communicate with the UK-DMC-1 satellite and to be capable of providing IP and DTN

connectivity between the ground stations and the GRC local network. NASA provided the routers and DTN bundle agents to USN.

The USN ground stations are located in Alaska, Hawaii and Australia. All three ground stations are operational. All ground stations were tested and can now receive both low-rate (38.4 kbps) IP-based operations telemetry and high-rate (8.134 Mbps) IP-based remote sensing imagery transmissions, multiplexed with telemetry, from the UK-DMC satellite.

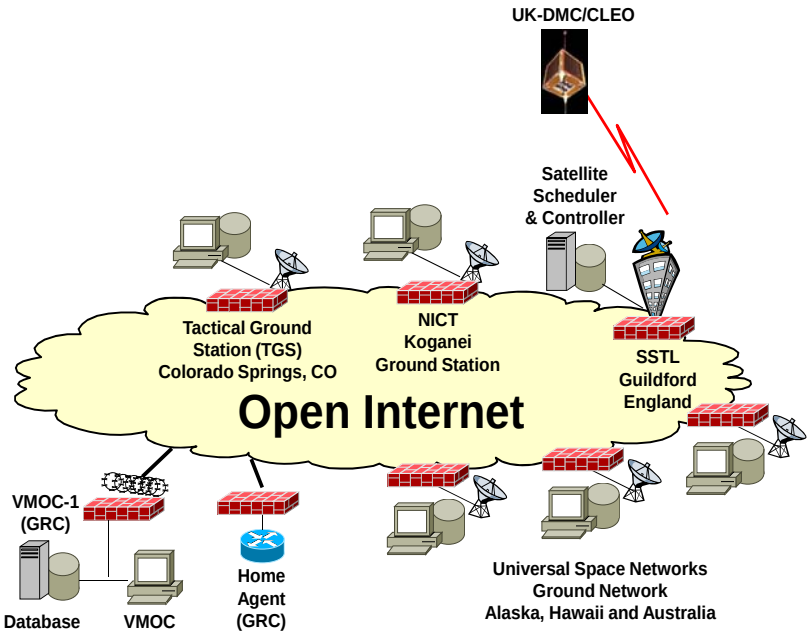


Figure 2: Space/Ground Network

III. Automated Service Agreements

The Concept of Operations for the Secure, Autonomous, Integrated Space/Ground Sensor webs, illustrated in Figure 1, requires access to space-based assets using multiple ground stations. Furthermore, the nature of the system development requires secure autonomous machine-to-machine scheduling of such assets. These autonomous, automated service agreements enable NASA to obtain near real-time access to space-based assets. To demonstrate secure autonomous machine-to-machine scheduling, General Dynamics, under contract to NASA, developed and implemented algorithms and code necessary to perform secure, autonomous, automatic scheduling of SSTL's UK-DMC-1 and SSTL and USN's ground assets within its Virtual Mission Operations Center (VMOC) software.

The basic operations flow is shown in Figure 3. Some event, such a volcano eruption, earthquake, tsunami or flood, is sensed by a remote sensor web. The remote sensor web sends an event trigger to the VMOC. The VMOC notes the location of the event and determines what space-based resources are available. In our example, only one space-based asset is available, the

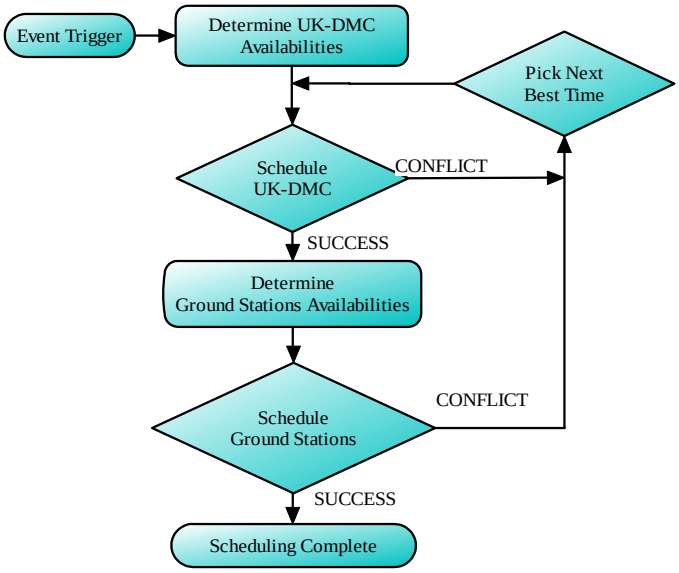


Figure 3: Machine-to-Machine Autonomous Scheduling

UK-DMC-1 satellite. The VMOC then negotiates with SSTL for availability of that asset. Once availability is determined, the VMOC determines what ground support infrastructure is available for both commanding and data retrieval. The VMOC then attempts to schedule these ground assets. If a conflict exists, the process is re-initiated, otherwise, the assets are scheduled and commanding and data retrieval is performed. Once the space-based sensor data has been downloaded and delivered and is made available via the VMOC, the VMOC will notify the end users as to the availability and location of such data.

General Dynamics' implementation of the Secure Autonomous Automated Scheduling (SAAS) project consisted of monitoring the United States Geographical Survey (USGS) earthquake notification system for sensor triggers, automatically scheduling an image acquisition of the target area via SSTL's UK-DMC-1 satellite and downloading the acquired image to the General-Dynamics-developed Virtual Mission Operation Center (VMOC) at NASA's Glenn Research Center (GRC), for access by SAAS VMOC users. The aim was to reduce the time between notification and availability of the image, by using multiple ground stations with both scheduled upload and payload download capability, as well as to demonstrate the ability to perform SAAS of on-orbit assets, triggered by available sensor webs. The system is documented in NASA Contractor Report NASA/CR-2010-216097.[10]

The SAAS project was developed in a phased approach, initially utilizing the SSTL ground station and Mission Planning System (MPS) web services interface and escalating to the utilization of additional Universal Space Network (USN) ground stations located in Alaska, Hawaii and Australia for both scheduled upload and image download. The SAAS Project phases are:

- Phase 1: VMOC requests imaging opportunities from a simulated SSTL MPS via the web service. The result is a valid schedule that is not acted upon. Tasking is simulated and a substitute raw image file will be made available via FTP for retrieval by the GRC VMOC. A further service will be made available for the VMOC to process the raw image to a single co-registered Tagged Image File Format (TIFF) image. This processing service will apply across all four Phases. Phase I was completed in July of 2009.
- Phase 2: VMOC requests imaging opportunities from the live SSTL MPS via the web service, subject to availability, tasking the UK-DMC-1 through SSTL's ground station to acquire the raw image file which will be downloaded to SSTL and made available via FTP.
- Phase 3: VMOC requests imaging opportunities from SSTL MPS via the web service identifying the ground station to receive the download image, subject to availability. VMOC will task UK-DMC-1 through SSTL's ground station to acquire the raw image file. This will be broadcast from UK-DMC-1 to the identified ground station and made available via FTP.
- Phase 4: VMOC requests imaging opportunities from SSTL MPS via the web service identifying the individual ground station to upload the schedule and potentially a different ground station to receive the broadcast download image, subject to availability. VMOC will upload the schedule file to UK-DMC-1 through the previously identified U/L ground station to acquire the raw image file. This will be transmitted from UKDMC-1 to the identified D/L ground station and made available via FTP.

For all phases of the SAAS project, the GRC VMOC provides the interface with the USGS earthquake website for triggering of SAAS of the UKDMC-1 satellite. The VMOC also provides the SAAS user interface for accessing the resultant imagery from the satellite.

IV. Glenn Research Center VMOC Overview

The GRC SAAS VMOC consists of five Adobe® ColdFusion® applications (Admin, Tactical, Mission, USN Ground and SSTL Ground Apps) contained within a website container [Figure 4]. Each application interfaces with all other apps and the outside world via Application Program Interfaces (API's) and each appropriate application provides a User Interface (UI) via the web site container to the SAAS VMOC user (not all UI's shown for clarity). The Tactical and Mission Applications also interface with Analytical Graphics, Incorporated (AGI) Satellite Tool Kit® (STK) models for necessary satellite, sensor, target and ground station contact information.

The main GRC SAAS VMOC page [Figure 5] provides the user with a hierarchical menu structure to access each of the SAAS VMOC applications (that have User Interfaces). The main page also provides a status of the VMOC applications and VMOC connections and a list of current users online.

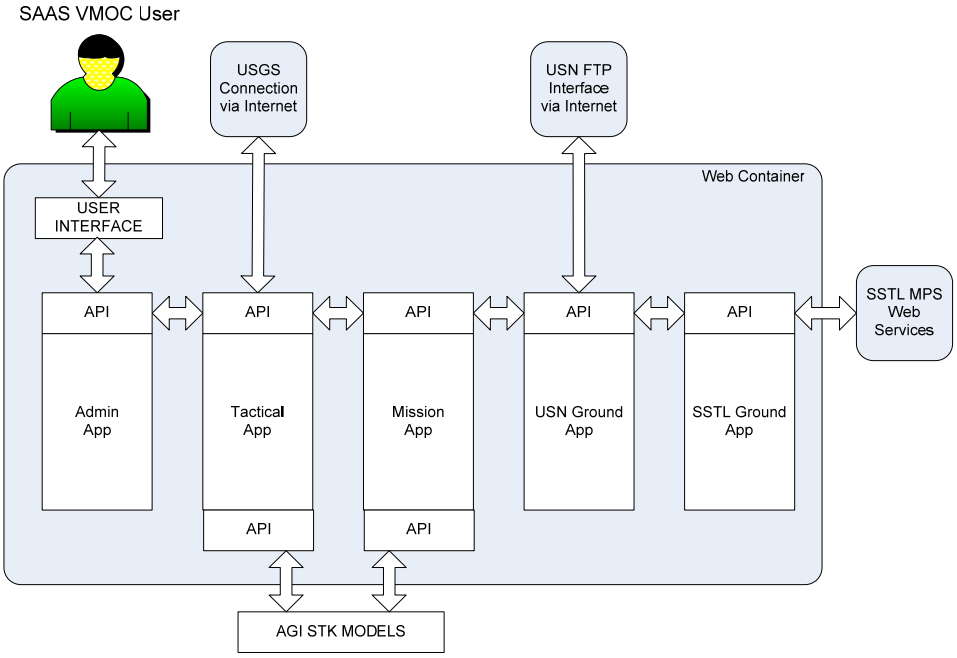


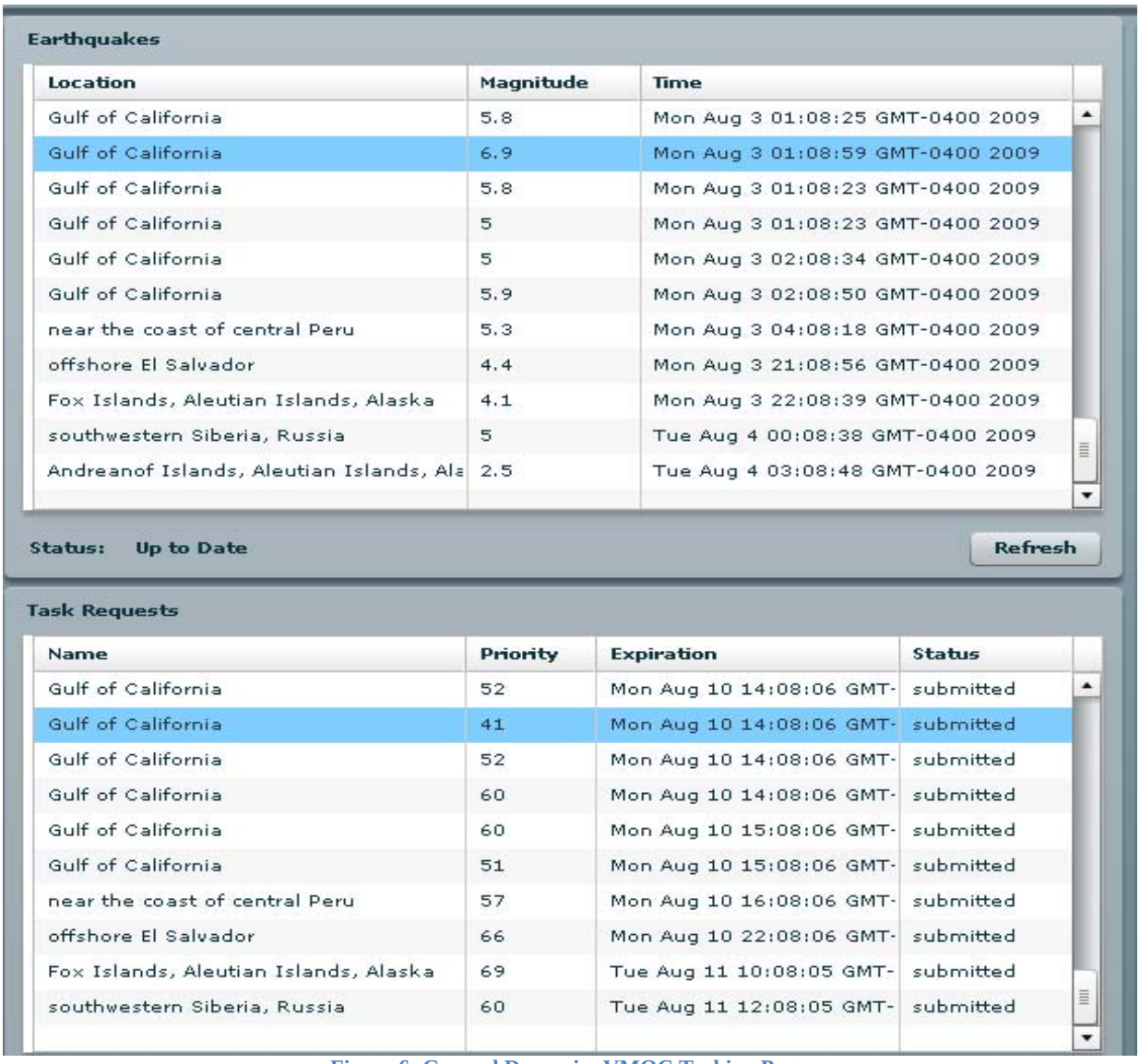
Figure 4 GRC SAAS VMOC Structure

Figure 5 GRC SAAS VMOC Main Page

V. SAAS-Phase 1 Demonstrated

The GRC SAAS VMOC Administration, Tactical, Mission and SSTL applications were all exercised during a SAAS Phase 1 demonstration in July 2009. Selected earthquake events (as defined in the Earthquake Admin Interface) were successfully collected and presented to the user via the Earthquake Tasks interface. Imaging task requests were automatically created by the Mission Application, including ground station up/down link contact availability information. The Mission Application successfully negotiated with the SSTL MPS and determined possible up/down link contact tasking and imaging collection times. These collection opportunities were presented to the user via the "UK-DMC Collection Management" interface, allowing the SAAS user to "authorize" collections for execution. During the Phase 1 demonstration, actual uplink load contacts, image collections and downlink contacts were not performed. All other user interfaces were also successfully demonstrated.

Figures 6 and 7 are from the GRC SAAS VMOC that performs automated tasking. The VMOC is currently administratively set to record all seismic activity above 2.5 on the Richter scale and task anything above 4.0 [Figure 6]. These are settable parameters with low values being used in order to obtain a large dataset for demonstration and debug. When a user highlights one of the locations, it will be shown on the mapping function [Figure 7].



Earthquakes

Location	Magnitude	Time
Gulf of California	5.8	Mon Aug 3 01:08:25 GMT-0400 2009
Gulf of California	6.9	Mon Aug 3 01:08:59 GMT-0400 2009
Gulf of California	5.8	Mon Aug 3 01:08:23 GMT-0400 2009
Gulf of California	5	Mon Aug 3 01:08:23 GMT-0400 2009
Gulf of California	5	Mon Aug 3 02:08:34 GMT-0400 2009
Gulf of California	5.9	Mon Aug 3 02:08:50 GMT-0400 2009
near the coast of central Peru	5.3	Mon Aug 3 04:08:18 GMT-0400 2009
offshore El Salvador	4.4	Mon Aug 3 21:08:56 GMT-0400 2009
Fox Islands, Aleutian Islands, Alaska	4.1	Mon Aug 3 22:08:39 GMT-0400 2009
southwestern Siberia, Russia	5	Tue Aug 4 00:08:38 GMT-0400 2009
Andreanof Islands, Aleutian Islands, Ala	2.5	Tue Aug 4 03:08:48 GMT-0400 2009

Status: Up to Date

Refresh

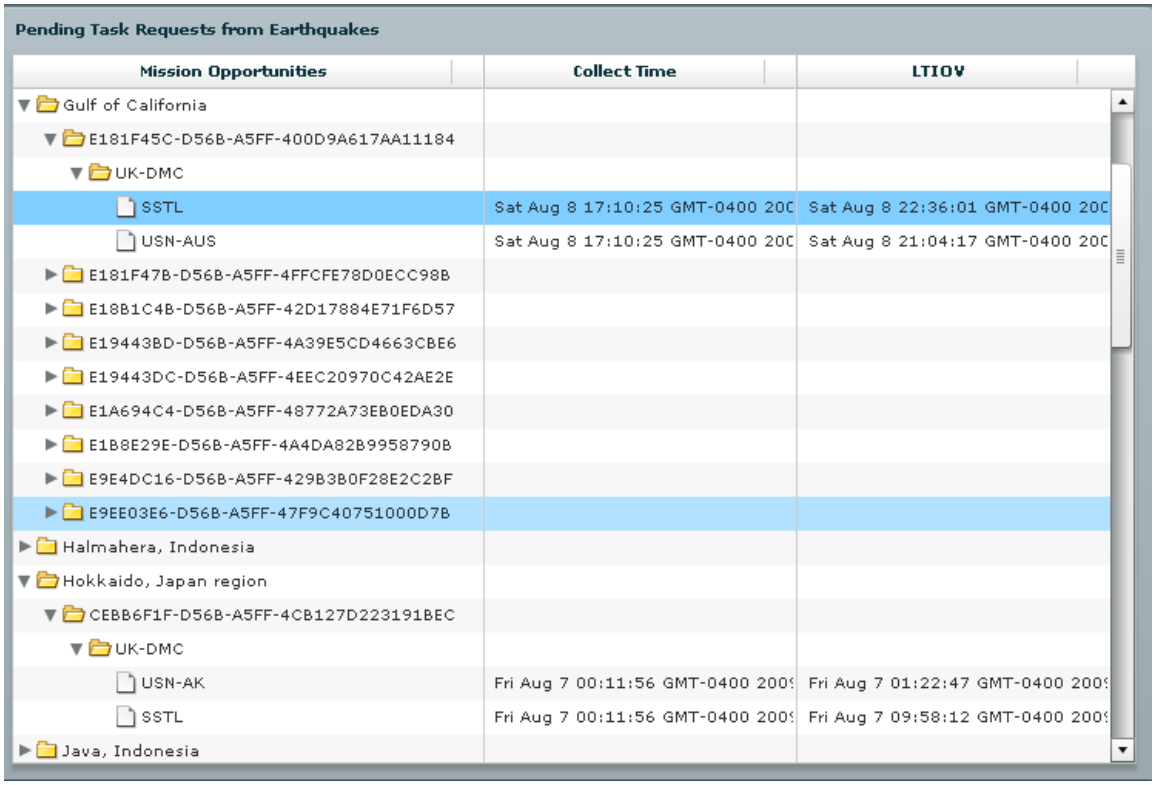
Task Requests

Name	Priority	Expiration	Status
Gulf of California	52	Mon Aug 10 14:08:06 GMT-	submitted
Gulf of California	41	Mon Aug 10 14:08:06 GMT-	submitted
Gulf of California	52	Mon Aug 10 14:08:06 GMT-	submitted
Gulf of California	60	Mon Aug 10 14:08:06 GMT-	submitted
Gulf of California	60	Mon Aug 10 15:08:06 GMT-	submitted
Gulf of California	51	Mon Aug 10 15:08:06 GMT-	submitted
near the coast of central Peru	57	Mon Aug 10 16:08:06 GMT-	submitted
offshore El Salvador	66	Mon Aug 10 22:08:06 GMT-	submitted
Fox Islands, Aleutian Islands, Alaska	69	Tue Aug 11 10:08:05 GMT-	submitted
southwestern Siberia, Russia	60	Tue Aug 11 12:08:05 GMT-	submitted

Figure 6: General Dynamics VMOC Tasking Page

Figure 7: Map showing location of item picked from the Tasking Page

Figure 8 shows the pending task requests. Notice that the operator is given the opportunity to select which ground stations one may wish to use to download the imagery. For the particular example selected, the Bay of California 6.9 earthquake, if one were to use the USN-Australia station, one could obtain the imagery approximately 90 minutes sooner. This data was obtained on August 5, 2009. Note, the next following available opportunity for the UK-DMC-1 to take an image of the Bay of California was Saturday, August 8th at 17:10 UTC. This availability is a combination of when the UN-DMC1 will pass over the Bay of California and when the UK-DMC-1 is available as it may have been tasked for other imagery prior to our request.

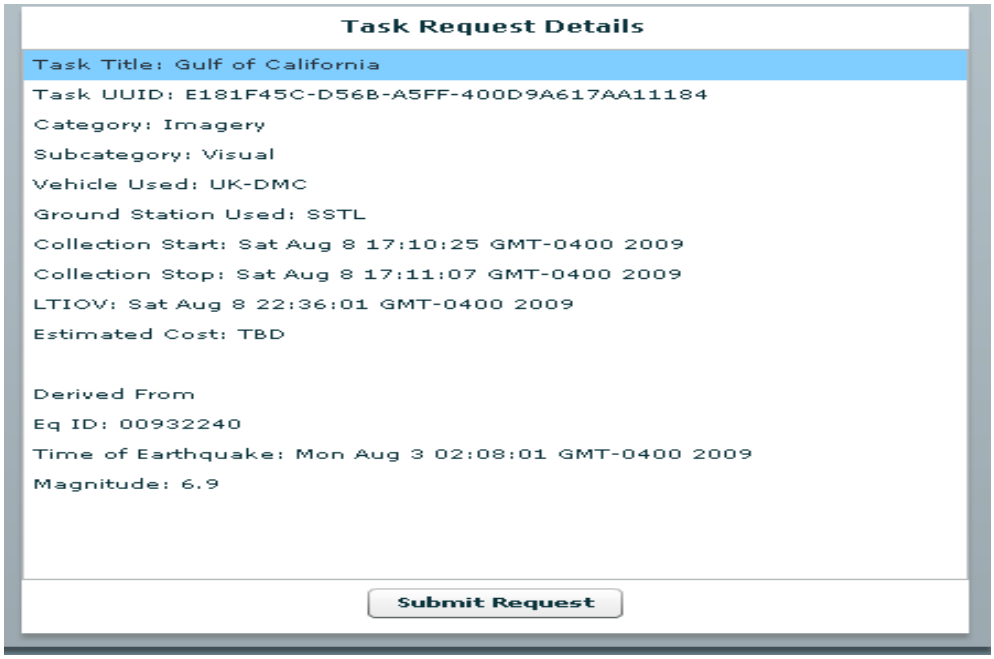


Pending Task Requests from Earthquakes

Mission Opportunities	Collect Time	LTIOV
Gulf of California		
E181F45C-D56B-A5FF-400D9A617AA11184		
UK-DMC		
SSTL	Sat Aug 8 17:10:25 GMT-0400 20C	Sat Aug 8 22:36:01 GMT-0400 20C
USN-AUS	Sat Aug 8 17:10:25 GMT-0400 20C	Sat Aug 8 21:04:17 GMT-0400 20C
E181F47B-D56B-A5FF-4FFCFE78D0ECC98B		
E18B1C4B-D56B-A5FF-42D17884E71F6D57		
E19443BD-D56B-A5FF-4A39E5CD4663CBE6		
E19443DC-D56B-A5FF-4EEC20970C42AE2E		
E1A694C4-D56B-A5FF-48772A73EB0EDA30		
E1B8E29E-D56B-A5FF-4A4DA82B9958790B		
E9E4DC16-D56B-A5FF-429B3B0F28E2C2BF		
E9EE03E6-D56B-A5FF-47F9C40751000D7B		
Halmahera, Indonesia		
Hokkaido, Japan region		
CEBB6F1F-D56B-A5FF-4CB127D223191BEC		
UK-DMC		
USN-AK	Fri Aug 7 00:11:56 GMT-0400 200	Fri Aug 7 01:22:47 GMT-0400 200
SSTL	Fri Aug 7 00:11:56 GMT-0400 200	Fri Aug 7 09:58:12 GMT-0400 200
Java, Indonesia		

Figure 8: Pending Task Requests

Figure 9 shows detailed information of the selected event. Furthermore, Figure 9 is the screen used to actually submit the request (and to eventually get charged for the request). Note, there is a field available to provide an estimated cost for executing the request in order to ensure the user is aware of the cost.



Task Request Details

Task Title: Gulf of California
Task UUID: E181F45C-D56B-A5FF-400D9A617AA11184
Category: Imagery
Subcategory: Visual
Vehicle Used: UK-DMC
Ground Station Used: SSTL
Collection Start: Sat Aug 8 17:10:25 GMT-0400 2009
Collection Stop: Sat Aug 8 17:11:07 GMT-0400 2009
LTIOV: Sat Aug 8 22:36:01 GMT-0400 2009
Estimated Cost: TBD

Derived From
Eq ID: 00932240
Time of Earthquake: Mon Aug 3 02:08:01 GMT-0400 2009
Magnitude: 6.9

Submit Request

Figure 9: Task Request Details and Submission

VI. Utilizing Other VMOC Capabilities

VMOC capabilities were utilized to support USN Ground station troubleshooting. The original GRC VMOC was utilized to both provide UK-DMC to Ground station contact information and also to verify successful telemetry downlinks. Since the VMOC access is via the Internet, multiple users with account access to the VMOC could simultaneously view telemetry and tune ground station equipment parameters in real-time (e.g. transmit power, Doppler compensation).

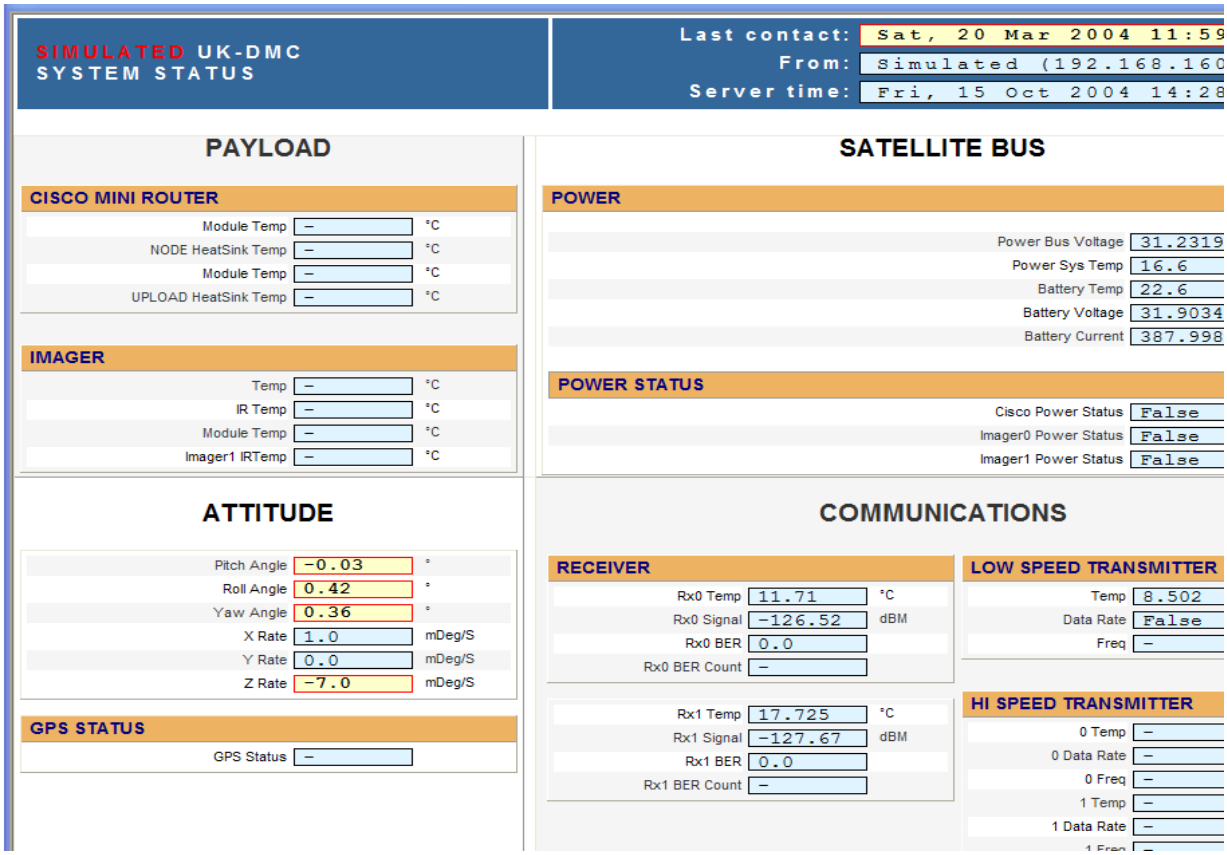


Figure 10: 2004 VMOC Telemetry Page

VII. Future Work

The core technology has been demonstrated in Phase I and is in place for automated scheduling of ground and space-based assets. In order to show complete automation of event trigger to sensor collection and data distribution, it is highly desirable to complete all aspects of this work including: development and demonstration of collection and downlink of images via the SSTL ground station (Phase II); automated downlink of data via USN ground stations; and both uplink load and downlink via any available ground stations (Phases III and IV).

Additional space assets could be brought into the network. Currently only the UK-DMC-1satellite is utilized. This is primarily due to SSTL's willingness to experiment with new protocols and techniques as well as the ease of interconnecting DMC-capable ground stations to the Internet, as all aspects of the DMC satellites and ground stations are Internet-Protocol-compliant.

VIII. Department of Defense use of the VMOC

The Department of Defense (DOD) expanded VMOC for scheduling and tasking various sensor platforms and handling requests via its Space Apportionment for Effect (SAFE) project,. In SAFE, the VMOC automated the Joint Space Tasking Order (JSTO) process, and issued the test JSTO to the Spacecraft Operations Center for implementation—all through a standard secure web environment.[11]

IX. Summary

Since 2004, NASA has been utilizing General Dynamics' Virtual Mission Operations Center as a secure portal for access to spacecraft telemetry and real-time control of a space-based asset using Internet technologies. We have continued expanding the functionality of the VMOC to include full autonomous machine-to-machine automated scheduling of third party assets. Major aspects of the concept of fully automating sensing an event-trigger, scheduling a space-based sensor to collect data, and data distribution have been successfully demonstrated. Use of multiple ground stations to increase contact times was also demonstrated, albeit, currently via a manually-initiated process. The space and ground network infrastructure was developed using commercially available assets. All communications were performed using commercial-off-the-shelf Internet Protocols with store-and-forward accomplished using the DTN experimental bundling protocol. This infrastructure remains in place for future development.

References

[1] IRIS Global Seismographic Network, January 2010, http://www.iris.edu/hq/programs/gsn

[2] Ivancic, W., "Large file transfers using multiple ground stations - Test Results 30 Sept and 01 Oct 2009," email to Internet Research Task Force DTN research group mailing list, January 2010, http://mailman.dtnrg.org/pipermail/dtn-interest/2009-October/004228.html

[3] Wood, L., Eddy. W., Wes, Ivancic, W., McKim, J., Jackson, C., "Saratoga: a Delay-Tolerant Networking Convergence Layer with Efficient Link Utilization." International Workshop on Space and Satellite Communications (IWSSC '07), Salzburg, Austria, 13-14 September 2007

[4] Ivancic, W., Stewart, D., Shell, D., Wood, L., Paulsen, P. ,Jackson, C., Hodgson, D., Northam, J., Bean, N., Miller, E., Graves, M., Kurisaki. L., "Secure, Network-Centric Operations of a Space-Based Asset: Cisco Router in Low-Earth Orbit (CLEO) and Virtual Mission Operations Center (VMOC)," NASA/TM-2005-213556, May 2005.

[5] Ivancic, W., Stewart, D., Wood, L., Jackson, C., Northam, J., Wilhelm, J., "IPv6 and IPSec Tests of a Space-Based Asset, the Cisco router in Low Earth Orbit (CLEO)," NASA/TM.2008-215203, May 2008.

[6] Wood, L., Ivancic, I., Hodgson, D., Miller E., Conner, B., Lynch, S., Jackson, C., da Silva Curiel, A., Cooke, D., Shell, D., Walke, J., Stewart, D., " Using Internet Nodes and Routers Onboard Satellites" International Journal of Satellite Communications and Networking, vol. 25 issue 2, pp. 195-216, March/April 2007.

[7] Wood, L., Ivancic, W., Eddy, W., Stewart, D., Northam, J., Jackson, C., "Investigating Operation of the Internet in Orbit: Five Years of Collaboration Around CLEO," IEEE Communications Society Satellite and Space Communications Technical Committee newsletter, vol. 18 no. 2, pp. 10-11, November 2008.

[8] Scott, K., and Burleigh, S., "Bundle Protocol Specification," IETF RFC 5050, experimental, November 2007.

[9] Wood, L., Ivancic, I., Eddy. W., Stewart, D., Northam, J., Jackson, C., da Silva Curiel, A., "Use of the Delay-Tolerant Networking Bundle Protocol from Space," IAC-08-B2.3.10, 59th International Astronautical Congress, Glasgow, September 2008.

[10] Walke, J., Dikeman, L., Sage, S., Miller, E., "Secure Autonomous Automated Scheduling (SAAS)-Phase 1 Final Report," NASA/CR-2010-216097, October 29, 2009.

[11] Miller, E., Hurley, M., Medina, O., Hopkins, J., Lane, R., Veglio, R., Kirkham, A., Ivancic, W., Jones, B., Risty, R., "Virtual Mission Operations Center (VMOC) Development and Experimentation," 5th Responsive Space Conference, April 23-26 2007, Los Angeles, CA.