CLEO AND VMOC: ENABLING WARFIGHTERS TO TASK SPACE PAYLOADS

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ABSTRACT

CLEO, the Cisco router in low Earth orbit, is a secondary experimental payload onboard the UK-DMC disaster-monitoring consortium remote-sensing small satellite built by Surrey Satellite Technology Ltd (SSTL). That router in space, its mobile networking capabilities, and the satellite's imaging capabilities have been proven as part of a demonstration and evaluation of VMOC, the Virtual Mission Operations Center, a joint US governmental/DoD initiative using Nautilus Horizon software from General Dynamics. The combination of the CLEO and VMOC initiatives together provides a framework to define, test, and field a 'system of systems' based on the Internet Protocol (IP), capable of supporting secure distributed mission operations of IP-based platforms and sensors. VMOC is an Internet-enabled secure application that provides a user-friendly interface which enables both trained and untrained operators in the field to access database satellite imagery, and allows users to task and command space assets. VMOC receives live telemetry from the UK-DMC satellite via multiple Internet-enabled ground stations and uses high-order, emerging Internet standards for web services to request SSTL's own mission planning system schedule Earth images to be taken by the UK-DMC satellite. VMOC accesses the CLEO router onboard the UK-DMC satellite via SSTL's own ground station in Guildford, UK, and via Universal Space Network's ground station at North Pole, AK. The primary VMOC server is located in the AF Center for Research Support (CERES) on Schriever AFB, CO, with a backup VMOC server located at NASA Glenn Research Center in Ohio. The Home Agent for mobile routing to CLEO through any ground station, providing a permanent point of contact for access, is also located at NASA Glenn. For the demonstration the Army Space Support Element Toolset was deployed to Vandenberg AFB, CA, which served as the field location and Internet access site during testing and evaluation of VMOC and CLEO.

We describe VMOC and the CLEO router in orbit. We summarize the Vandenberg demonstration and the metrics on which VMOC was evaluated, as well as ongoing testing. We also describe how shared use of the Internet Protocol, IP, allowed this demonstration to successfully use and leverage existing equipment and infrastructure across the Internet that was not originally intended for this purpose, bringing a user application, a satellite and a router in space together to meet the needs of Net-centric Operations.

INTRODUCTION

On 27 September 2003, a Cisco Systems mobile access router was launched into low Earth orbit as a secondary experimental payload onboard the UK–DMC disaster monitoring constellation satellite built by SSTL. The UK-DMC satellite's primary mission is to provide Landsat-style, mid-resolution, remote sensing imagery. This satellite operates within the Disaster Monitoring Constellation (DMC) of small satellites built by SSTL for a number of collaborating countries.

The CLEO router became the focal point of an experiment involving a wide range of organizations across civil, commercial and defense sectors. In June 2004, after lying dormant while the satellite's primary payloads were commissioned and used, the router was used as the IP-compliant, space-based asset and evaluated as part of the field assessment of the OSD Rapid Acquisition Initiative Net Centricity (RAI-NC) "Virtual Mission Operations Center" demonstration at Vandenberg Air Force Base.[1-3]

Together, CLEO and VMOC successfully completed a number of tests that demonstrate the effectiveness of IP communication to satellites for the warfighter.

CLEO: CISCO ROUTER IN LOW EARTH ORBIT

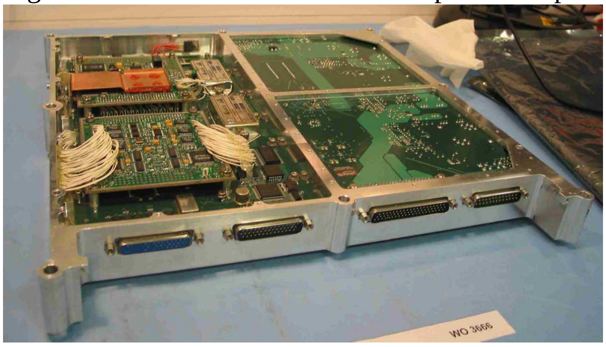
The router deployed onboard the UK–DMC satellite consists of two PC-104/Plus-based circuit boards:

the PowerPC-based Cisco 3251 Mobile Access Router (MAR) processor card, and a four-port serial mobile interface card (SMIC).

Although this mobile access router is capable of supporting 100Mbps Fast Ethernet connections, there is no Ethernet onboard the UK-DMC satellite, so 8.1Mbps serial interfaces are used to connect to other payloads.[4] This is designed to match the use of an 8.1Mbps serial interface on a Cisco 2621 router receiving the output of the downlink from the modem in each ground station.

The router cards flown [fig. 1] received some hardware modifications for the space environment:

1. The cards were flow-soldered with lead-based, rather than tin-based, solder. Although tin is environmentally friendlier than lead, tin solder is particularly prone to growing "whiskers" in a vacuum, leading to shorted circuits.
2. All terrestrial plastic connectors which would warp in temperature extremes were removed and replaced with point-to-point soldered wiring. Unused components around those connectors were removed.
3. A large heatsink was attached to the main processor, and a brace conducted heat away to the payload's aluminum chassis.
4. Wet electrolytic capacitors with vents that would leak in a vacuum were replaced with dry capacitors.
5. The clock battery was removed to avoid explosion and leakage; the router was later configured in orbit to use Network Time Protocol (NTP) in order to automatically learn the correct time from a ground-based server whenever it is powered up.



At back left: router card with heatsink brace in place.
At front left: serial card is connected to payloads via half-width motherboard under cards.

Figure 1. CLEO assembly mounted in rack tray.

The cards were mounted on an SSTL-designed 'motherboard' that provided connectivity and power control. The completed assembly took up half a payload tray. The router assembly successfully survived full system flight-level qualification testing (vibration, vacuum and thermal cycling) on its first attempt. This included a temperature range of -60 to +35°C and a vacuum of less than 1×10^{-3}Pa. Total power consumption of the combined unit is approximately 10 W at 5 V.

The router cards flown were *not* modified in any way to provide increased radiation tolerance, and did not use space-qualified parts. The router software was also unmodified – a commercial release of Cisco's IOS Internetworking Operating System software (12.2(11)YQ of September 2002) was flown. This use of commercially-available hardware and software is unrestricted by ITAR regulations.

Access to configure CLEO on orbit via internetworked ground stations has been via the console serial port, telnet, secure shell (ssh), and secured web interfaces. As an experimental payload added to the UK-DMC satellite, the router is not connected directly to the satellite downlink. Instead, when testing the router during a ten-minute pass over a ground station, the onboard computers form a virtual star topology centered on the router, and frames are passed from the router to an onboard computer to be copied out to the downlink.

While being tested during satellite passes over groundstations, CLEO has operated as expected on orbit, both in power draw and performance. Although CLEO is far less power-hungry than traditional 19" rack-mounted routers, the 10W the assembly draws, combined with the 10W taken by the 8Mbps S-band downlink when that is operational, forms a significant proportion of the UK-DMC satellite's 30W power budget. CLEO is powered off when not being tested in order to conserve available satellite power and battery life.

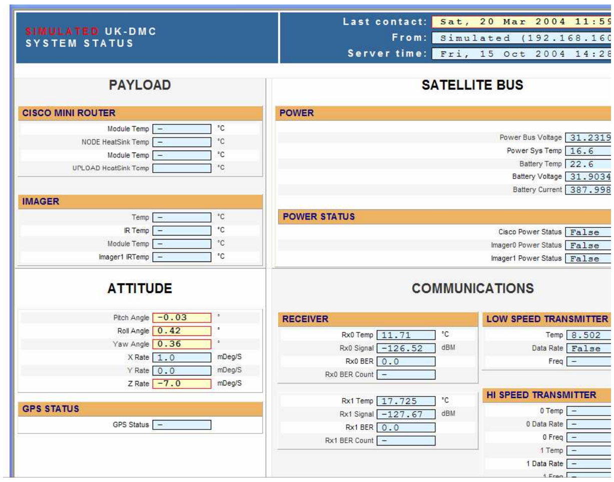
VMOC: VIRTUAL MISSION OPERATIONS CENTER

The General Dynamics (GD) Nautilus Horizon software provides a framework for the mission partners to define, test, and field an IP-based command and control (C2) system capable of supporting secure distributed mission operations of any IP-based platform or sensor. Here, the VMOC provides a framework to connect remote space operators directly to an orbiting space payload, using Internet protocols to acquire satellite telemetry data and imagery, dynamically task satellite payloads, and undertake telemetry, tracking and command (TT&C) of an on-orbit satellite asset (the CLEO router) – all through a user-friendly web-based interface requiring little operator training [fig. 2].

With the satellite ground stations tied to the Internet, a VMOC becomes the control element that can orchestrate the tie between the user and the spacecraft.

The GD VMOC performs a number of functions:

1. enables system operators and data users to be remote from ground stations
2. verifies individual users and their authorizations.
3. establishes a secure user session with the platform.
4. performs user and command prioritization and contention control; the ‘Nautilus’ name reflects the multiple levels of tiered security implemented.
5. applies mission rules and performs command appropriateness tests.
6. relays data directly to the remote user without human intervention.
7. provides a knowledge database and is designed to enable interaction with other, similar systems.
8. provides an encrypted gateway for access by “unsophisticated” remote users of sensor data.



Here, a web page shows live UK-DMC satellite telemetry relayed by a ground station during a pass.

Figure 2. Screenshot of VMOC web interface.

The VMOC supporting the Vandenberg exercise was implemented as a geographically distributed, dual, hot-standby operations center. The primary VMOC was located in CERES on Schriever Air Force Base, CO, with the backup VMOC located at NASA GRC in Cleveland, Ohio.

THE SSTL MISSION PLANNING SYSTEM

The DMC small satellite constellation, within which the UK-DMC satellite operates, is a co-coordinated collection of ground and space assets owned by multiple organizations.[5] To provide C2 across the constellation, SSTL developed a secure distributed Mission Planning System (MPS) with distributed systems interfaces and a web-based end user interface. It is the responsibility of this MPS to:

1. receive and collate image requests for areas of interest.
2. perform orbit propagation.
3. prioritize and schedule acquisition opportunities based on request priorities and asset constraints.
4. automatically generate spacecraft and ground station command schedules to execute the image acquisition plan.

Use of each country’s spacecraft and ground station in the DMC is planned through an independent MPS that holds its master schedule. Each MPS can communicate with its peers over the public IP Internet, via standard web services (the SOAP Simple Object Access Protocol), through secure encrypted tunnels (SSL secure sockets layer) and using a Virtual Private Network based on Cisco PIX firewalls. With minor modification to the application programming interface (API), the existing web services interface was used to negotiate unplanned programmed image requests received in real-time from VMOC, using XML-RPC (remote procedure calls) and SOAP. The VMOC was allocated an appropriate priority so as not to interrupt commercial imaging. This live interaction between distributed planning systems was demonstrated successfully, with the UK-DMC MPS executing and delivering on VMOC image requests during and after testing and demonstrations at Vandenberg.

The GD VMOC models satellite orbits, visibility and availability. However, for a satellite operated by a third party, this model turns out to be approximate at best, as the GD VMOC is unaware of other parties' conflicting scheduling requirements or of power demands onboard the UK-DMC, or of details of imaging capabilities or storage limitations. A later iteration of the GD VMOC/SSTL MPS interface handed off more functionality to the autonomous SSTL MPS, moving away from hard absolute commanding to a higher-level softer request negotiation model.

UK-DMC IMAGERY AND NETWORKING

Each of the sun-synchronous-orbiting DMC satellites, including the UK-DMC satellite, carries an optical imaging payload developed by SSTL to provide a minimum of 32m ground resolution with a uniquely wide swath width of over 640 km. (Some DMC satellites provide better resolutions.) All payloads use green, red and near-infrared bands equivalent to Landsat TM+ bands 2, 3 and 4.

Images are stored onboard the UK-DMC in two PowerPC-based computers designed by SSTL, with 1 and 0.5 gigabytes of RAM respectively. During passes over groundstations, images are copied as files to the SSTL mission operations center or partner groundstations via an 8.1Mbps S-band downlink. There is also a low-rate 38.4kbps downlink to provide satellite status telemetry when the high-rate downlink is not active, while commands are received via a low-rate uplink at 9600bps. All links carry IP packets inside frame relay and HDLC encapsulation. This protocol encapsulation is an engineering choice made as a result of experience gained previously testing IP use with SSTL's satellites.[6]

Image transfer from satellite to ground station uses a custom rate-based UDP file transfer protocol designed and implemented by SSTL.[7] This protocol gives smaller code footprint size and increased performance when compared to SSTL's earlier implementation of the CCSDS File Delivery Protocol (CFDP), allowing more image data to be transferred during a pass. Payloads are given dedicated access to the downlink according to an uploaded schedule, and flood the downlink with packets to transfer as much data as possible in the time available during a pass.

The UK-DMC on-board computer (OBC) that controls the platform provided telemetry about the status of the satellite as a UDP broadcast stream. This IP stack is written in-house by SSTL and considered experimental; the OBC can also run AX.25-based communications software (and the other DMC satellites do so, while their payload computers are based on IP). This AX.25 fallback use reflects SSTL's long amateur radio experience and heritage.

The ground stations belonging to SSTL and to the partner countries owning other satellites in the Disaster Monitoring Consortium are networked together using IP. PCs on each ground station Ethernet local area networks (LANs) run applications for dealing with satellite telemetry and images. As the ground-station LANs are connected to the public Internet, network security is needed. Cisco PIX firewalls are used.

TESTING CLEO WITH VMOC

The Cisco router in Low Earth Orbit (CLEO) project, funded by Cisco Systems, and the VMOC project, funded by the RAI-NC program, are separate but complementary in their shared use of the Internet Protocol, and the overlapping organizational groups involved in these projects gain mutual benefit from working together. The VMOC and router testing was a collaborative experiment centered on the Air Force, the Army and NASA Glenn Research Center, and involving other organizations. NASA Glenn worked with Cisco to test the CLEO router under a mutually beneficial Space Act agreement.

The Army and Air Force Space Battle Labs provided support and performed the overall metrics collection and evaluation as part of the OSD-sponsored VMOC effort. The VMOC demonstrations occurred 'in the field' during 1-13 June 2004, followed by a three-day demonstration during 14-16 June, all from an Army Space Support Element Toolset (SSET) deployed in field conditions at Vandenberg Air Force Base in California [fig. 3].

Operators at the Vandenberg SSET specified areas of the Earth, received satellite images and telemetry, and commanded the router.

Figure 3. The Space Support Element during VMOC testing at Vandenberg AFB.

The SSET provided Internet connectivity through commercial SATCOM. Army and Air Force field users relied on mobile routing to communicate across the Internet via a home agent at NASA Glenn's headquarters in Cleveland, Ohio, to the Cisco router onboard the satellite via the supporting SSTL ground station [fig. 4]. The addressing for SSTL's existing ground station network design is flat, with all ground stations numbered similarly, and addresses are translated to the outside world if necessary; support for mobile networking had to be added without disrupting either SSTL's existing network operations or the primary imaging mission.

Use of mobile routing provided CLEO with a static IP address that the VMOC could use to command the spaceborne router, entirely independent of the ground station currently visible to the satellite.

The VMOC demonstration supported multiple field users, with varying missions and priorities, acquiring sensor and TT&C data from the UK-DMC satellite.

VMOC allowed users to connect directly to a payload onboard the UK-DMC satellite (the CLEO router) via the Internet and mobile routing via NASA Glenn. VMOC also demonstrated storage and retrieval of satellite imagery data on demand via a knowledge management database. Imagery annotation tools enhanced collaboration between users. The use of Internet protocols throughout in all components of this demonstration allowed specific net-centric C2 capabilities to be demonstrated and evaluated:

1. Warfighter access to sensor data.
2. Information pull from a platform or sensor by warfighters.
3. Information pull from existing databases by field users.
4. Suitability of IP for operations.

The final metrics analysis resulting from the Vandenberg testing showed that the VMOC demonstration met its objectives, and that use of IP allows quick and simple field operations under a variety of circumstances.

The VMOC's ease of use became quickly apparent during the demonstration. Operators required little training on the VMOC's web-based, user-intuitive interface in order to perform space taskings and operations. This can result in training cost avoidance. It also provides confidence in user acceptance as net-centric technologies are proliferated into the force.

The use of IP opens new avenues to enable users to access space capabilities previously closed off to distributed warfighters. Legacy systems in use by warfighters rely on stovepiped architectures limiting access, delaying information and lacking mobility. This demonstration has shown that distributed, geographically-separated users could access space sensors and platforms and share limited resources as long as they have connectivity and authorization. Using VMOC, an airman in a field operations center could be checking satellite platform battery voltages and available power while a soldier riding in a Humvee requests an image from that satellite's sensor.

Both the CLEO router and the IP-based VMOC software were able to build upon SSTL's adoption of IP and the IP-based infrastructure of the satellites and ground stations that was being built, and so could treat the satellites as nodes on a large IP-based network that seamlessly merged space and ground assets. The capabilities demonstrated here are evolutionary and desirable outcomes emerging from all parties adopting use of the Internet Protocol and being able to collaborate fully technically as a result.

OTHER DEMONSTRATIONS

Further demonstrations of CLEO and VMOC have been held.

On 5 November 2004, VMOC/MPS imaging request operations, using the SSTL ground station to task the UK-DMC satellite, were demonstrated at Air Force Space Command Headquarters in Colorado Springs.

On 18 November 2004, further demonstrations took place to the leadership of Air Force Space Command during its Commanders' Conference in Los Angeles, CA. On 2 December 2004, the Joint VMOC team performed a similar demonstration to leadership from the Air Staff and Joint Staff in the Washington, DC area.

On 10 May 2005, a public demonstration of CLEO and VMOC was held at the AFEI Net-Centric Operations conference in Washington, DC, using the Universal Space Network (USN) Alaska ground station to access the router during two passes.

ONGOING DEVELOPMENT OF CLEO

Testing of the CLEO router continues only when the UK-DMC satellite is not otherwise tasked with its primary imaging mission. This testing relies on scheduled passes over the USN Alaska ground station to avoid using passes over SSTL's own ground station whose opportunity cost would detract from SSTL's normal operations and from the satellite's primary mission. Several passes per week used for accessing and configuring the router can be accomplished.

The CLEO Cisco router has been in space for over twenty months, and has been tested in orbit for over a year. CLEO has been powered up more than forty times for testing during passes over ground stations. There is interest in seeing how long this commercial, non-hardened computing device using non-space-qualified parts will last in low Earth orbit, and what total radiation dose it will tolerate.

CLEO's success in showing IOS router software in orbit has led to Cisco Systems taking the next step of porting IOS to a space-qualified radiation-hardened processor in the PowerPC family: the BAE750. This is a step to a hardened embedded router, whose hardware and interfaces would be very different from that of this CLEO demonstrator.

ONGOING DEVELOPMENT OF VMOC

General Dynamics' VMOC software will continue spiral development to enhance system interoperability and responsiveness, enhance situational awareness, facilitate "system of systems" solutions, and support automated machine-to-machine interactions.

An enhanced VMOC providing increased Application Programming Interfaces (APIs) is in preparation for the Air Force Space Battle Lab Theater Space Apportionment For Effect (TSAFE) demonstration that has been planned for February 2006.

CONCLUSIONS

The UK-DMC satellite demonstrates that handling satellite command and telemetry and data delivery based upon the Internet Protocol is possible and can be successful.

The CLEO experiment onboard the UK-DMC satellite has shown that a commercial off-the-shelf router can be adapted to and work in the space environment in low Earth orbit. The use of CLEO for mobile networking showed that mobile networking is a viable technology for networking across disparate and separate networks on two continents.

The use of VMOC with the SSTL mission planning system shows that a high-level "system of systems" approach to exchanging data, building on open standards, can allow independently-developed autonomous systems to interoperate with beneficial results.

The VMOC tests at Vandenberg successfully demonstrated use of CLEO and of the UK-DMC satellite, while showing the utility of mobile networking and Internet Protocol use for C2 for the warfighter.

ACKNOWLEDGMENTS

The efforts of the many collaborating participants in the CLEO and VMOC integration and testing are greatly appreciated. A detailed list of participants is given in the NASA technical memo describing testing the orbiting router.[8]

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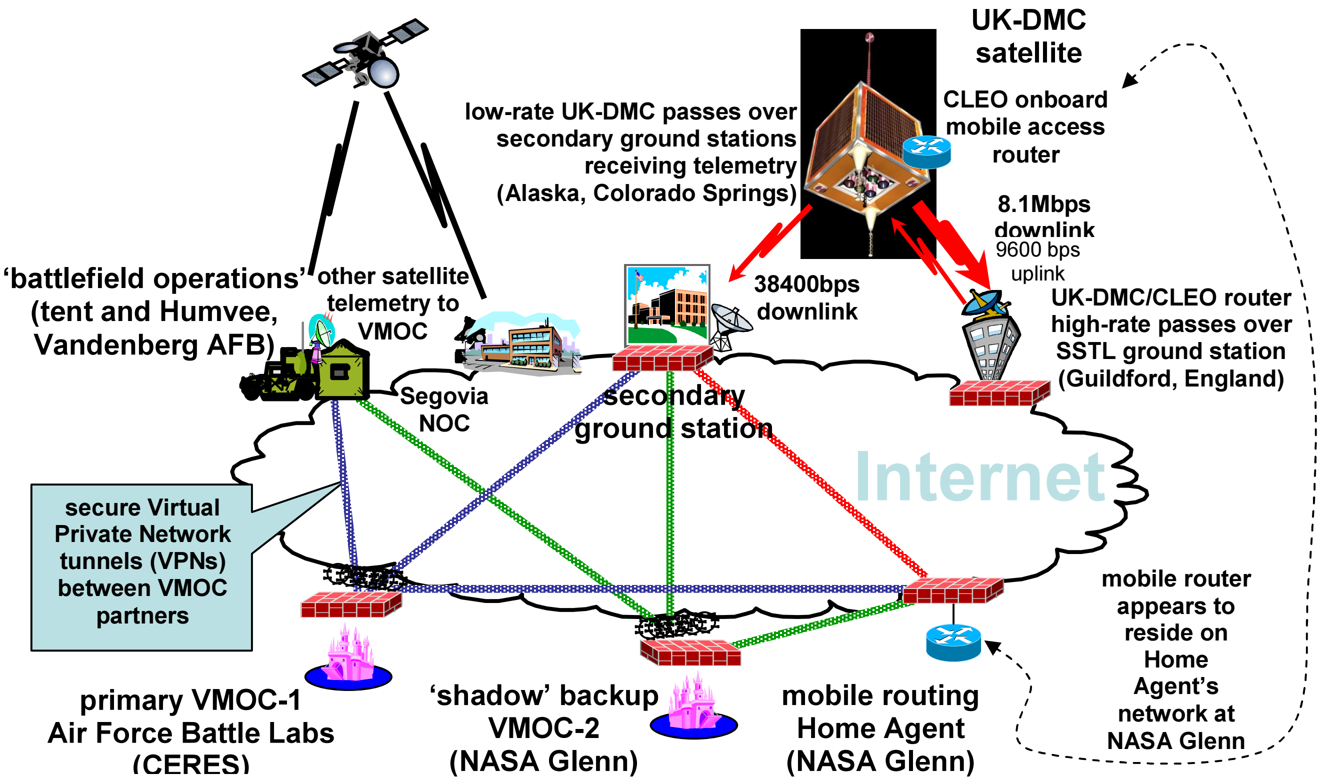

Figure 4. Network topology for the Vandenberg demonstration.