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# Adopting Internet Standards for Orbital Use

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## Abstract

After a year of testing and demonstrating a Cisco mobile access router intended for terrestrial use onboard the low-Earth-orbiting UK-DMC satellite as part of a larger merged ground/space IP-based internetwork, we reflect on and discuss the benefits and drawbacks of integration and standards reuse for small satellite missions. Benefits include ease of operation and the ability to leverage existing systems and infrastructure designed for general use, as well as reuse of existing, known, and well-understood security and operational models. Drawbacks include cases where integration work was needed to bridge the gaps in assumptions between different systems, and where performance considerations outweighed the benefits of reuse of pre-existing file transfer protocols. We find similarities with the terrestrial IP networks whose technologies we have adopted—and also some significant differences in operational models and assumptions that must be considered.

## 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 Surrey Satellite Technology Ltd. (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.

That Cisco router was able to be integrated into the UK-DMC satellite because of engineering study work done previously that had adopted the Internet Protocol, IP, for communication with onboard network stacks, and which had built the ground station network around a Cisco router and standard serial interfaces using HDLC (ref. 1).

The onboard router was tested as part of a wider internetworking 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 that was evaluated as part of the evaluation of the OSD Rapid Acquisition Initiative Net Centricity (RAI-NC) "Virtual Mission Operations Center" (VMOC) demonstration that took place at Vandenberg Air Force Base (ref. 2).

## Cisco Router in Low Earth Orbit

The Cisco router in Low Earth Orbit (CLEO) 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 100 Mbps Fast Ethernet connections, there is no Ethernet onboard the UK-DMC satellite, and 8.1 Mbps serial interfaces are used to connect to other payloads (ref. 3). The onboard serial links are designed to match the use of an 8.1 Mbps serial interface on a Cisco 2621 router receiving the output of the downlink from the modem in each ground station; the downlink is extended to each payload as required.

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.

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 $1\times10^{-3}$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.

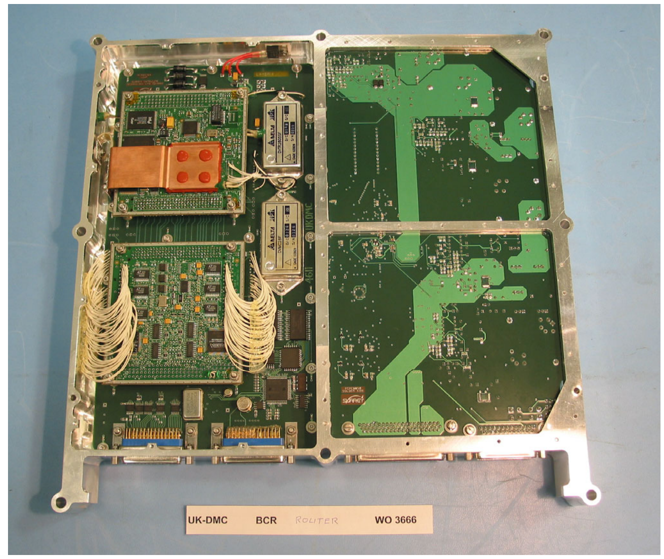


Figure 1.—CLEO assembly mounted in rack tray. At back left: router card with heatsink brace in place. At front left: serial card is connected to payloads via half-width motherboard under cards.

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 in. rack-mounted routers, the 10 W the assembly draws, combined with the 10 W taken by the 8 Mbps S-band downlink when that is operational, forms a significant proportion of the UK-DMC satellite's 30 W power budget. CLEO is powered off when not being tested in order to conserve available satellite power and battery life.

## UK-DMC Imagery and Networking

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 (ref. 4). 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 32 m 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. These are the Solid-State Data Recorders (SSDRs). During passes over groundstations, images are copied as files to the SSTL mission operations center or partner groundstations via an 8.1 Mbps S-band downlink. 8.1 Mbps was chosen as it is the maximum rate supported by the serial interface on the Cisco routers to be used in the ground stations; this is also the rate at which the onboard router communicates via its serial links. There is also a low-rate 38.4 kbps downlink to provide satellite status telemetry when the high-rate downlink is not active, while commands are received via a low-rate uplink at 9600 bps.

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 UoSAT-12 satellite (ref. 1).

Payloads are given dedicated access to the downlink according to an uploaded schedule, and must flood the downlink with packets to transfer as much data as possible in the limited time available during a pass. Image transfer from satellite to ground station uses a custom rate-based UDP-based file transfer protocol designed and implemented by SSTL (ref. 5). 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, so that the entire contents of an SSDR's memory can be downloaded, and the SSDR can then be turned off until its next use, in order to save power.

The UK-DMC on-board computer (OBC) that controls the platform provided telemetry about the status of the satellite as a UDP broadcast stream from its IP stack.

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.

## The SSTL Mission Planning System

To provide command and control across the disaster monitoring 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 (VPN). With little modification, that web services interface was used to negotiate unplanned programmed image requests received in real-time from the General Dynamics VMOC software used during internetwork tests, using well-understood network standards: 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.

## 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, as they are already compatible technically thanks to their shared use of common open standards. 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 (ref. 6). 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 to 13 June 2004, followed by a three-day demonstration during 14 to 16 June. Operators at the Vandenberg demonstration specified areas of the Earth, received satellite images and telemetry, and commanded the router.

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. 2). The addressing for SSTL's existing ground station network

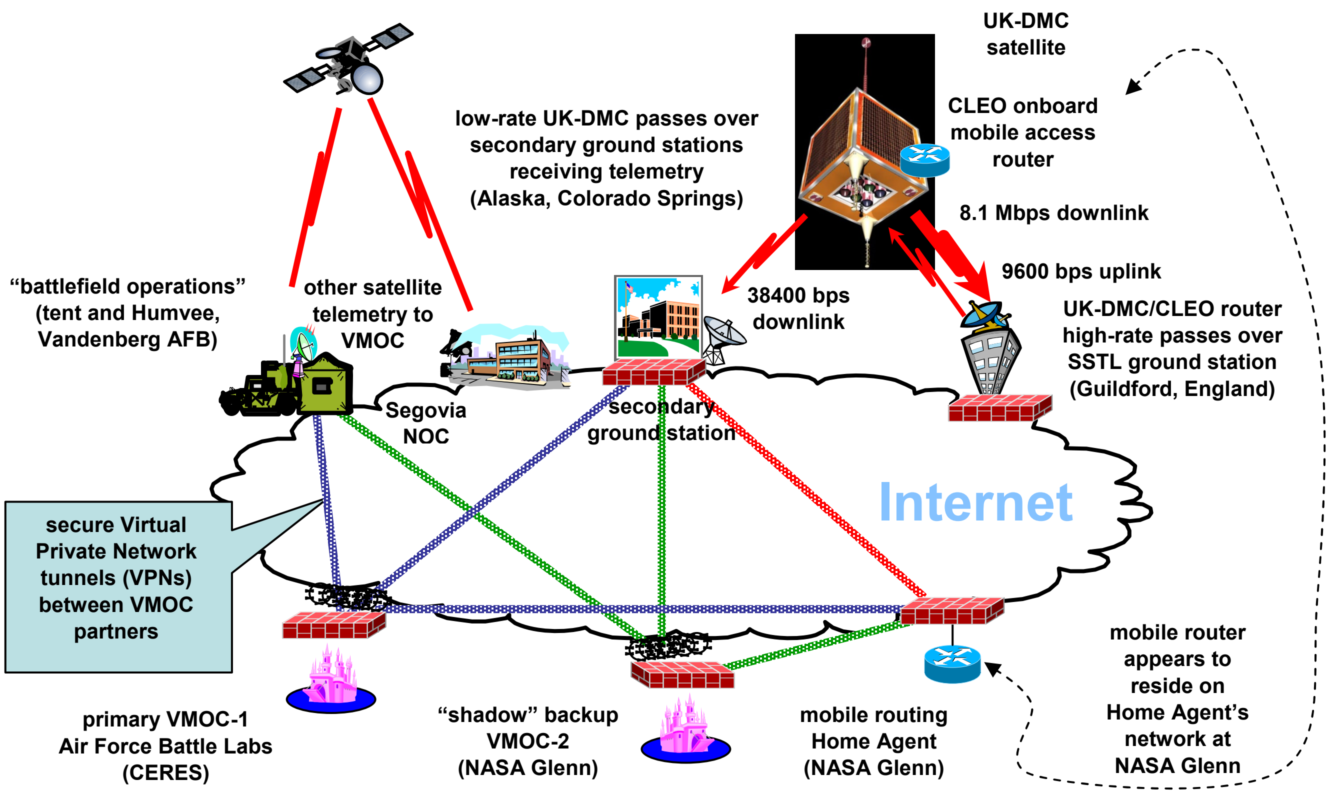


Figure 2.—Network topology for the Vandenberg demonstration.

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. CLEO can currently be accessed either via SSTL's own ground station in Guildford, England, or via the Universal Space Network ground station in Poker Flat, Alaska, which replicates the SSTL ground station and modem use.

Both the CLEO router and the IP-based VMOC software application 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; not as a result of any careful top-down long-term planning.

## Other Networking 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 Alaska ground station to access the router during two satellite passes.

## Lessons From Tests and Operation

An Internet router is good for arbitrating fairly between nodes competing for access to a link in order to provide multiplexed access to connectivity. This is the dominant terrestrial Internet mode of operation. But when you own and manage your own computers onboard your own small satellite, and you have the power budget and accessibility concerns of a small satellite, a coarser-grained scheduling paradigm becomes much more attractive. You download data files from an onboard computer payload, and once it holds nothing more of interest you simply turn that computer off until it is next needed. Each computer is scheduled dedicated access to the downlink, and other engineering design decisions fall out from that. (Although scheduling of payload on times and access to the multiplexer is timetabled in advance, a "soft scheduling" model is used where the schedule is uploaded as a textfile to the platform's onboard computer to interpret and follow, and the schedule for future events can be updated, altered and uploaded during any pass prior to events taking place.)

The dominant terrestrial Internet mode of operation would be more attractive for large shared platforms (ISS, Hubble), or for payloads onboard permanently accessible geostationary satellites with higher bandwidth links.

In the terrestrial Internet, immediate end-to-end connectivity is important; the ability to reach another endpoint in a timely fashion. This is what makes the instant clickability of the web and audio and video streaming possible.

For a low-Earth-orbiting small satellite doing store-and-download that is not backhauled via connectivity through a geostationary transponder to download its images immediately after taking them, pass utilization—getting as much out of each pass over each ground station and available download time—dominates. This desire to download as much data as possible, in the case of the UK-DMC imaging requirements, led to the development of a custom network stack using the rate-based UDP transfer protocol, SSTL's Saratoga, in order to fill the downlink with image files and use the ten or so minutes of a pass as effectively as possible. The images were downloaded across a single link, the downlink, to a ground station, and no further. Saratoga's design lacks congestion control algorithms, making it unsuitable for widespread Internet use between any endhosts—while the TCP suitable for Internet use would not make efficient use of the available pass, and would be more effective for arbitrating between multiple competing onboard computers using a multiplexing, rather than the scheduling, model outlined above.

The image download model here is more analogous to e.g., application-level http proxy caching, where files are cached locally to avoid creating bottleneck-constrained long paths, and processed at the ground station cache, and then fetched on demand by terrestrial users. However, the end-to-end connectivity model still applies for real-time commanding (done by uploading scheduling files by TCP/IP, and for direct access to the onboard router) and for streaming telemetry (implemented as broadcast UDP from the satellite for the ground station LAN and repeated to select destinations via a unicast UDP reflector, but which could easily be implemented as multicast traffic.)

Even if a LEO imaging satellite used a geostationary transponder to communicate with a ground station for extended periods of time, power and link efficiency concerns and the desire to switch between scheduled payloads based on need would still encourage the adoption of rate-based transfer protocols rather than TCP, given TCP's well-known inefficiencies in adjusting to geostationary delays.

Adoption of terrestrial network technologies means necessary adoption of widespread terrestrial security paradigms, which are fortunately well-understood. SSTL's ground station LAN becomes an integral part of SSTL's corporate network, and is now managed in the same way by the same people. Cisco PIX firewalls were used to set up a Virtual Private Network (VPN) between ground stations. Link-level encryption of the UK-DMC satellite link might also be considered necessary, but was not done. Future SSTL missions are considering link encryption.

Given the limited pass times and availability of the onboard router, it was extremely helpful to have a ground-based testbed, combining the sister engineering model of the flight router with one of SSTL's SSDRs (fig. 3). This rack-mounted ground-based testbed is connected to a personal computer, which emulates the OBC.

This testbed was constructed after launch for NASA Glenn to gain familiarity with the SSTL network environment and payloads, and to enable NASA Glenn to determine successful and safe configurations for the onboard router that would not interfere with SSTL's primary mission. Working configurations were copied to the router in orbit once tested and validated on the ground-based testbed. This enabled effective use of the limited on-orbit testing time, enabling the ability to configure the on-orbit router essentially from nothing in few passes.

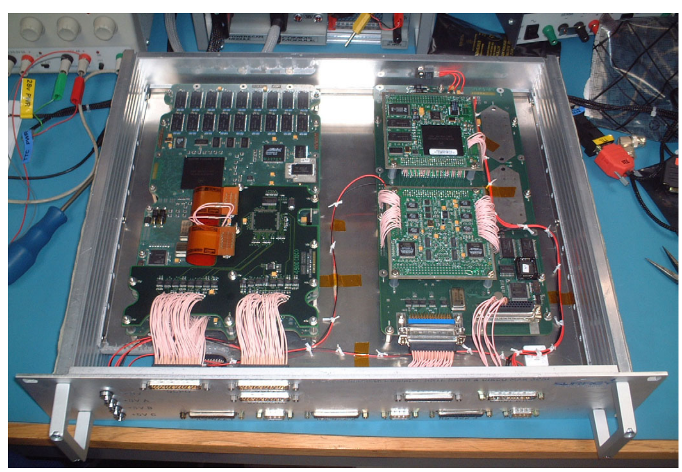

Figure 3.—Ground-based testbed. On left: SSTL SSDR assembly. On right: router assembly.

## Problems Encountered

Technical problems encountered during testing and operating the router payload were relatively minor.

While in the Vandenberg tent, the VMOC operators found that they were getting satellite passes finishing a couple of minutes earlier than expected—because their Solaris workstations were not configured to use the network to query time server using Network Time Protocol (NTP) to update their local clocks. When operating actual satellites, it is helpful to know the actual time.

The UK-DMC satellite was temporarily unavailable between the testing campaign and the demonstration, due to a problem encountered by its on-board computer (OBC) requiring that computer to be reset. As a knock-on effect, SSTL had been rebooting its SSDRs daily to work around a problem with their serial driver software in coming out of pass-through mode to support the router, so access to the router was unavailable until both the OBC and SSDRs had been commanded to reboot on subsequent passes. Given SSTL's soft scheduling methodology, rescheduling future events to take account of lost time is relatively straightforward.

The OBC 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 IP based). This AX.25 fallback use reflects SSTL's long amateur radio experience and heritage. SSTL has moved the UK-DMC OBC back to AX.25 while debugging its internal software, removing a source of UDP-based telemetry during passes.

The Universal Space Network Alaska ground station used to receive low-rate telemetry during the Vandenberg demonstration took some time to become fully operational; it was discovered that the high-speed downlink signal was too strong for and saturated the Comtech modem in use, requiring additional attenuation to be inserted. That attenuation was achieved by the Alaska RF chain working off right-circular polarisation, while the signal is left-circular polarised. Occasional multipath distortion resulting from this led to occasional poor link quality during passes over Alaska.

The General Dynamics 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. The GD VMOC can only prioritise requirements that it is aware of, resolving conflicts between and for its own users. The VMOC's assumptions were not always applicable to shared assets over which the VMOC does not have absolute control. 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 by VMOC to a higher-level softer request negotiation model.

The CLEO Cisco router performed entirely as expected.

## 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.

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. Several passes per week used for accessing and configuring the router can be accomplished.

The success of CLEO, showing the use of Cisco's 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 would be used in a fully space-qualified embedded router.

## Conclusions

The UK-DMC satellite demonstrates that handling satellite command and telemetry and data delivery based upon the Internet Protocol and related commercially-used standards 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, building on commercially-used standards that had already been adopted for their benefits. 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 approach to exchanging data between complex systems, building on open standards, can allow independently-developed autonomous systems to interoperate with beneficial results.

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