Operating a terrestrial Internet router onboard and alongside a small satellite

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Abstract

After twenty months of flying, testing and demonstrating a Cisco mobile access router, originally designed for terrestrial use, onboard the low-Earth-orbiting UK-DMC satellite as part of a larger merged ground/space IP-based internetwork, we use our experience to examine 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 with a large set of latent capabilities to draw on when needed, as well as the familiarity that comes from 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 have been taken to small satellites -- and also some significant differences between the two in operational models and assumptions that must be borne in mind.

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.

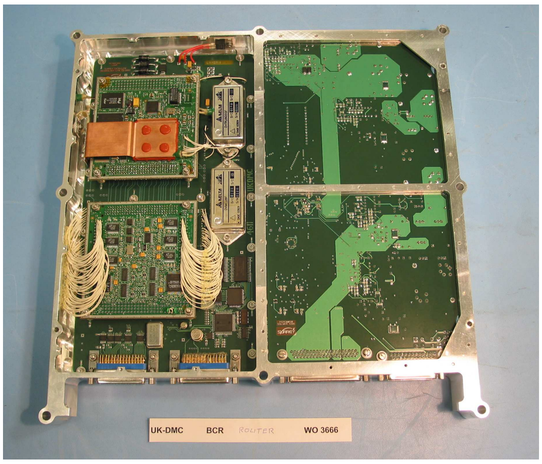
That Cisco router was able to be integrated into the UK-DMC satellite because of engineering study work done previously that had adopted the Internet Protocol, IP, for communication with onboard network stacks, and which had built communication between the satellite and ground station network around a Cisco router and common serial interfaces.[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 formed 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.[2]

The 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 100Mbps Fast Ethernet connections, there is no Ethernet onboard the UK-DMC satellite, and 8.1Mbps serial interfaces are used to connect to other payloads.[2]



back left: router card with heatsink brace.
front left: serial card interfaced to payloads
via half-width motherboard.

Figure 1: CLEO assembly in payload tray

The onboard serial links are 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 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 considered more environmentally friendly 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 the risks of explosion or leakage. The router was later configured in orbit to use Network Time Protocol (NTP) to learn the time from a ground-based server whenever the router is turned on. This made timestamps of saved configuration files in the router’s 32MB flash filesystem useful.

The two 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 10W at 5V. 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 US ITAR (International Traffic in Arms Regulations).

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 other onboard computers form a virtual star topology centered on the router, and frames from the router are ‘passed through’ an onboard computer to be copied out to the downlink.

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.

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 8.1Mbps S-band downlink when that is operational, forms a significant proportion of the UK-DMC satellite’s available 30W 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.[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 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. 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 8.1Mbps S-band downlink. 8.1Mbps 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 38.4kbps 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 (High-level Data Link Control) 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.[1] Without that previous work, done in cooperation with NASA Goddard, to lay down use of commercial networking standards by SSTL's satellite and ground station network, integration of the router into the satellite would have been much more difficult.

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.[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 on-board computer (OBC) that controls the UK-DMC 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's Ethernet local area network (LAN) 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 that was 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.

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

Users in the field 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. 3]. 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. CLEO can currently be accessed either via SSTL’s own ground station in Guildford, England, or via the Universal Space Network (USN) 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

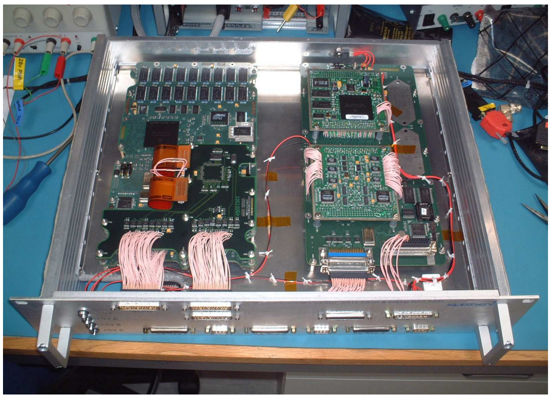
Further demonstrations of CLEO and VMOC have been held.

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, CLEO and VMOC were demonstrated at the AFEI Net-Centric Operations Conference in Washington, DC.



Left: SSDR assembly. Right: router assembly.
Figure 2: Ground-based testbed

This used the USN Alaska ground station to access the router during two satellite passes.

Lessons from tests and operations

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 possible the instant clickability of the web and audio and video streaming, as well as remote connectivity via secure shell (ssh).

On a low-Earth-orbiting small satellite, which is doing store-and-forward download and 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 the operating model. The desire to download as much imaging data as possible led to development of a custom network stack using a 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, 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, 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 and high bandwidth-delay products.

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. 2]. This rack-mounted ground-based testbed is connected to a personal computer, which emulates the OBC.

This testbed was intended 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 resulted in effective use of the limited on-orbit testing time, enabling the ability to configure the on-orbit router, essentially from nothing, in few passes. The testbed was constructed after launch.

Some problems during operations

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

While in the field at Vandenberg, the VMOC operators found that satellite passes over ground stations were finishing a couple of minutes earlier than expected – because their Solaris workstations had not been configured to use the network to query a time server using Network Time Protocol (NTP) to update their local clocks. When operating real satellites, it helps to know the real time.

Pass-through software, needed for packets from the router to reach the ground, was written and uploaded to the SSTL SSDRs after launch. Before this software was uploaded the router was only available via direct console access.

The UK-DMC satellite was temporarily unavailable between the testing campaign and the demonstration, due to a problem encountered by its platform 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. With SSTL’s soft scheduling methodology, rescheduling future events to take account of lost time is relatively straightforward.

Configuration of CLEO was done entirely on orbit after launch, and was able to use latent capabilities of the IOS router software whose use had not been anticipated earlier. For example, the existing onboard topology is such that the OBC and router share a serial interface and address; when both are on, only one device should respond to messages addressed to that interface. It was straightforward to configure an access control list on the router’s interface to limit its output so that only the OBC responded to the shared address. Testing this configuration change on the ground-based testbed and then repeating the commands on orbit during a pass to prevent this was far simpler than recompiling and uploading the OBC software would have been.

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 SSDR computers are IP based). This AX.25 fallback use reflects SSTL's long amateur radio experience and heritage. SSTL has since moved the UK-DMC OBC back to AX.25 while debugging its internal software, temporarily removing a source of UDP-based telemetry during passes. While using AX.25, the OBC is turned off during high-rate passes to avoid inadvertently responding to IP traffic it misinterprets as AX.25 frames.

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 EF Data CDM-600 modem while 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. Multipath distortion resulting from this led to experiencing poor link quality during a number of passes over the Alaska ground station. This problem is now well-understood and needs to be corrected for further deployment.

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 onboard router performed entirely as intended.

Further developments with CLEO

Testing of the CLEO router continues only when the UK-DMC satellite is not otherwise tasked with its primary imaging mission. This ongoing 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 primary mission. Several passes per week can be undertaken to access and test the router.

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. This is a step to a hardened embedded router, whose hardware and interfaces would be very different from that of this CLEO demonstrator.

Conclusions

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

The UK-DMC satellite has demonstrated 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 Disaster Monitoring Constellation of small satellites shows that IP-based data delivery of remote sensing image files from orbit can be relied upon to create a useful imaging service.

Use of VMOC with the SSTL mission planning system shows that a successful high-level approach to exchanging data between complex systems can build on open standards based around the Internet Protocol.

Acknowledgments

We greatly appreciate the combined efforts of the many collaborating commercial, civil and military participants in the CLEO and VMOC integration and testing.

A detailed list of participants in the testing campaign is given in the NASA technical memo describing testing the CLEO orbiting router.[6]

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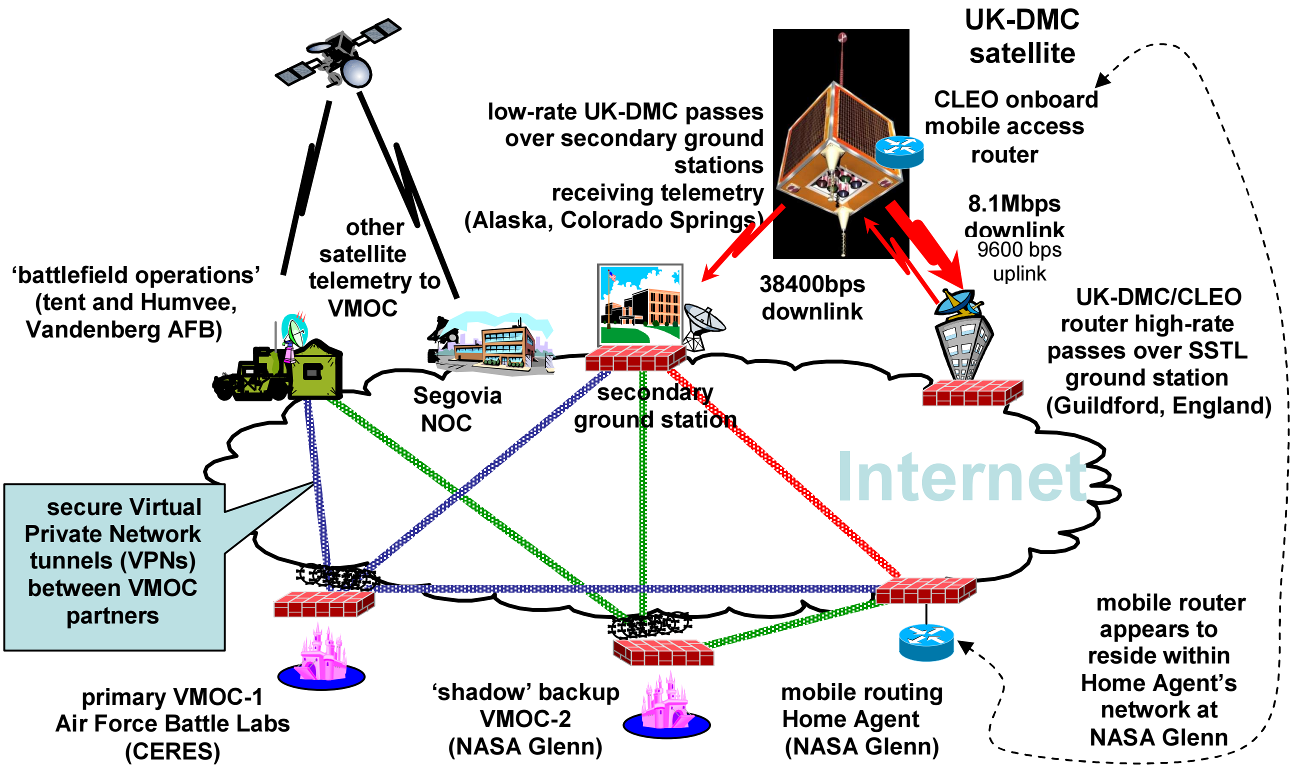

Figure 3: Network topology for the Vandenberg demonstration