Using Internet nodes and routers onboard satellites

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Abstract: An Internet router was integrated into the UK-DMC remote-sensing satellite as a secondary experimental payload. This commercial product has been orbiting in space for over three years. We describe the integration of the router and satellite and the successful on-orbit testing of the router, which took place using the Virtual Mission Operations Center (VMOC) application as part of a larger systems internetworking exercise. Placing this Cisco router in Low Earth Orbit (CLEO) onboard a small satellite is one step towards extending the terrestrial networking model to the near-Earth space environment as part of a merged space-ground architecture.

Key words: Internet, router, UK-DMC, satellite, HDLC, Frame Relay, IP, UDP

1. 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-class, mid-resolution, remote sensing imagery. This satellite operates within the growing Disaster Monitoring Constellation (DMC) of small satellites that has been built by SSTL for a number of collaborating countries.[1]

The onboard router was tested as part of a larger internetworking experiment involving a wide range of organizations across civil, commercial and defence sectors. In June 2004, after lying dormant while primary payloads were commissioned and used, the onboard router acted as an Internet-Protocol compliant, space-based asset that played a part in the evaluation of the "Virtual Mission Operations Center" (VMOC) demonstration that took place at Vandenberg Air Force Base. VMOC is one of the US Office of the Secretary of Defense's Rapid Acquisition Initiative Net Centricity (OSD RAI-NC) pilot projects.[2]

The Cisco router was easily integrated into the UK-DMC satellite due to previous engineering work that had already adopted the Internet Protocol, IP, for communication between onboard IP network stacks and a ground station network that relies on a Cisco router with commercial serial interfaces.[3]

2. Extending the Internet to orbit

Satellites have been relaying Internet Protocol (IP) traffic since the 1970s,[4,5] but making an orbiting satellite an active part of the Internet is a more recent development. Several previous experiments that have placed Internet nodes on satellites are mentioned here.

In 1996, software uploaded to the STRV-1b satellite, tested by NASA's Jet Propulsion Lab, gave that satellite an IP address that could be used for experimental communication.[6]

In 2000, a TCP/IP stack was uploaded to SSTL's UoSAT-12 satellite, and experiments were run by NASA Goddard in collaboration with SSTL as part of the OMNI (Operating Missions as Nodes on the Internet) project.[3,7]

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SSTL used experience gained from the OMNI work by migrating from AX.25 towards IP and adopting IP for operation of their Disaster Monitoring Constellation (DMC) satellites, launched from Plesetsk in Siberia. AlSAT-1, the first of these satellites, was launched in November 2002.[8] The UK-DMC satellite, which carries the Cisco router, was launched alongside its sister satellites (BILSAT-1 and NigeriaSat-1) in September 2003. The Beijing-1 satellite joined the constellation in October 2005. Further satellites are planned.

SpaceDev's CHIPSat, which uses TCP/IP for all communications with ground stations, was launched for NASA from Vandenberg Air Force Base in January 2003.[9]

Internet devices have also been used in shirtsleeves environments in orbit by astronauts. For example, in 2001, Cisco's SoftPhone was used on a laptop PC onboard the space shuttle Atlantis, using voice over IP (VoIP) to talk across a local Ethernet LAN that was connected to the shuttle's custom equipment that communicated via TDRSS with NASA Johnson Space Center and the ground phones there.[10,11] The Russian International Space Station (ISS) module contains a terrestrial router and network.[12]

CCSDS protocols have been used by ESA and NASA for communication with a variety of orbiting and deep-space missions. The CCSDS link protocols can optionally be made to carry IP in a number of different ways.

3. Active network nodes on satellites

Traditionally, satellites do not possess routing functionality. With a 'bent-pipe' geostationary satellite, a satellite link is treated as just that: a single link in each direction between ground terminals. Although this 'link' consists of an uplink followed by amplification, frequency downshifting and a downlink returning the carried signal to the ground, the single satellite link budget combines all of these steps. There is a strong codependency between a signal's uplink and its downlink.

Often, even when demodulating or decoding a signal to baseband onboard the satellite, the relationship between the design of the uplink and that of the downlink remains very strong. This codependency can make for clarity of design and engineering optimization when the satellite transponder is used for its intended purpose. This coupling between uplink and downlink can also permit flexibility in use of the single established radio channel through both the uplink and downlink that results, e.g. in allowing ground terminals to use turbo coding across links using satellites deployed before turbo coding had been developed, without requiring any changes to the satellites.

However, a combined single link through a satellite limits overall flexibility of link use, terminal design, and thus the functionality of networking services that can be offered by available combined satellite capacity as a system. On-board processing (OBP) can decrease the uplink/downlink codependency. Completely breaking this dependency can increase the flexibility of use of available uplinks, downlinks, payloads and terminals in ways not envisaged by their original designers.

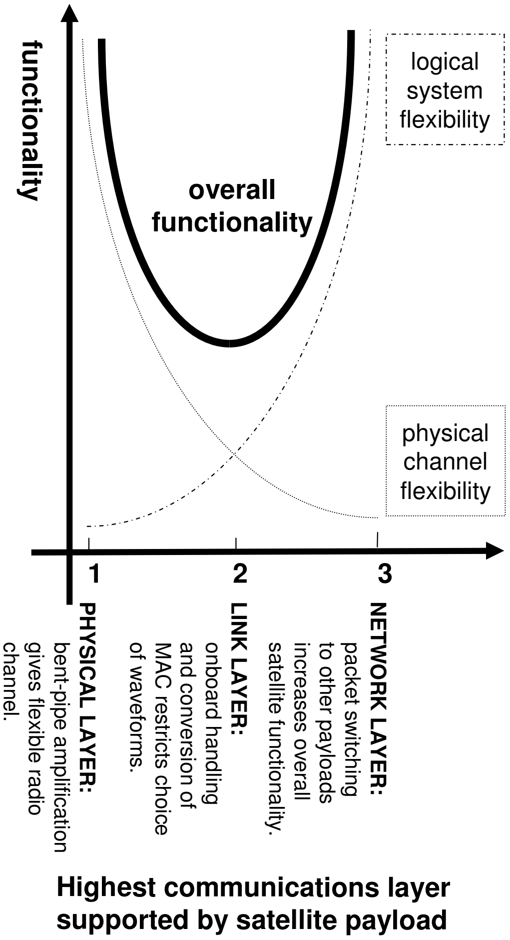

Figure 1: Flexibility/processing tradeoffs

Breaking this link dependency allows us to consider the evolution of the middle of these links: the satellite.

Introducing OBP with digital signal processing (DSP) constrains the air interfaces to predetermined waveforms, limiting the flexibility of use of the radio channel. This form of OBP can do e.g. onboard conversion between different media access control (MAC) link formats on the uplink and downlink, but limits the uplink and downlink to use of those chosen formats.

Leveraging use of OBP with frame and packet processing can introduce system-level logical flexibility, with more interaction between onboard transponders and payloads, compensating for the flexibility that has been lost at the physical layer in the radio channels. This tradeoff between radio and system flexibility is shown in fig. 1.

Being either completely ‘bent-pipe’, fully flexible in terms of waveforms that can be amplified and repeated, or being networked with smart payloads that are interconnected for system flexibility, offers benefits. The radio flexibility increases as we approach the bent-pipe amplification; the system flexibility increases as we approach networking.

We argue that a payload doing only on-board processing of only one type of waveform limits both the physical radio flexibility and future waveform choices that ground terminals can make, as it is no longer ‘bent-pipe’, while also not supporting networked payloads. Summing the independent frequency and system flexibility curves suggests that limited, isolated, on-board processing is the least flexible of these three approaches, as it constrains frequency flexibility to a fixed waveform while not embracing networking of payloads.

Increased onboard processing and switching capabilities on computationally 'smarter' satellites can introduce bridging and then networking functionality within and between payloads, and later between satellites with intersatellite links, in an evolutionary fashion.[13,14] The satellites would contain active network nodes that are linked together.

By operating a router onboard a satellite, we have shown that on-board processing is capable of packet switching and of performing as an active network node. This has led to interesting benefits for an overall system for command and control, and for integration with terrestrial networks, as shown by our tests from Vandenberg Air Force Base.

4. Cisco router in Low Earth Orbit

The Cisco router in Low Earth Orbit (CLEO), on the UK-DMC satellite, consists of just two 90 x 96 mm PC-104/Plus-based circuit boards:

- the Cisco 3251 Mobile Access Router Card (MARC), based around a PowerPC processor with a core speed of 210MHz;
- a Serial Mobile Interface Card (SMIC).

Although this mobile access router is capable of supporting 100Mbps Fast Ethernet connections, no Ethernet is used onboard the UK-DMC satellite, and the four serial interfaces on the SMIC card connect the CLEO router to other onboard computers.[15] These onboard serial links are designed to match the use of a serial interface on a commercial off-the-shelf Cisco 2621 router in each ground station that receives the output of the downlink from the modem at a maximum rate of 8.1Mbps. The downlink is extended to each payload as required.

The router cards flown as CLEO received some simple hardware modifications for the space environment:

1. The cards were flow-soldered with solder including lead, instead of pure tin solder. Although tin is considered more environmentally friendly than lead, pure tin solder is particularly prone to growing crystalline “whiskers”. Tin whiskers forming in free fall have led to shorted circuits and the loss of satellites.[16]
2. All terrestrial plastic ‘push to fit’ connectors, which would loosen during launch vibration and 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 conducts heat away to the aluminum chassis of the payload tray.
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 CLEO 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 provides connectivity and power control [fig. 2].

The completed CLEO assembly takes up just half of an SSTL payload tray; the modular design of SSTL satellites makes adding or altering payloads straightforward.

This router assembly passed full system-level flight qualification testing (vibration, vacuum and thermal cycling) at the first attempt. This included a temperature range of -60 to +35℃ and a partial vacuum of less than 1×10^{-3}Pa pressure. Total power consumption of the combined CLEO assembly is approximately 10W at 5V.

The router cards flown were *not* modified in any way for space to provide increased radiation tolerance, and did not use any space-qualified parts.

The router software was also unmodified for space — a commercial release of Cisco's IOS Internetworking Operating System software (version 12.2(11)YQ, released September 2002) was flown.

This use of commercially-available hardware and software is unrestricted by US ITAR (International Traffic in Arms Regulations) export rules.

As the router is an experimental payload added to the UK-DMC satellite, it is not connected directly to a satellite downlink. Instead, when testing the router during a pass of up to twelve minutes 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.

Although CLEO is far less power-hungry than traditional 19" rack-mounted routers, the 10W that the CLEO assembly draws, combined with the 10W taken by the 8.1Mbps S-band downlink when that is operational, forms a significant fraction of the UK-DMC satellite's available 30W power budget. CLEO is powered off when not being tested during available passes in order to conserve available satellite power and battery life.

While being tested during satellite passes over groundstations and autonomously in orbit, CLEO has operated as expected, in power draw, performance, and reliability.

5. The ground-based testbed

Given the limited pass times and availability of the onboard router, it was extremely helpful to have a ground-based testbed available. This rack-mounted testbed combines a sister engineering model of the flight mobile router with one of SSTL's Solid-State Data Recorder computers [fig. 3].

The testbed is connected to a personal computer, which emulates the on-board computer controlling the satellite platform. This testbed was intended for NASA Glenn to gain familiarity with SSTL's network environment and custom payloads, and to enable NASA Glenn to determine successful and safe configurations for the onboard router that would not interfere with SSTL's pre-existing use for the primary mission. NASA Glenn personnel had helped Cisco Systems define and develop its mobile router, so were already extremely familiar with the router. The testbed was constructed after launch.

Working configurations were copied to the router in orbit after being tested and validated for use on the ground-based testbed. This led to effective use of limited on-orbit testing time, enabling the ability to configure the on-orbit router, essentially from nothing, in few passes. Access to configure CLEO on orbit via internetworked ground stations was initially via its console serial port, which was used to bootstrap configuration of telnet, secure shell (ssh), and secured web interfaces.

6. UK-DMC imagery and networking

The UK-DMC satellite operates within the Disaster Monitoring small satellite constellation, which is a co-coordinated set of ground and space assets owned by multiple organizations.[17] The sun-synchronous-orbiting DMC satellites each carry an optical imaging payload, developed by SSTL, that provides a minimum of 32m ground sample distance (GSD) with a uniquely wide swath width of over 640 km. (Some DMC satellites can also provide better resolutions from other onboard imagers.) These imagers use green, red and near-infrared bands equivalent to Landsat TM+ (Thematic Mapper) bands 2, 3 and 4.

Images are recorded onboard the UK-DMC satellite in two SSTL-designed PowerPC-based computers, running at a core speed of 210MHz and with 1.0 and 0.5 gigabytes of RAM each; similar technology to CLEO. These are the Solid-State Data Recorders (SSDRs). There is also a slower 80MHz StrongArm-based SSDR, of older design, controlling a GPS reflectometry experiment.[18]

During passes over groundstations, recorded imagery data or reflectometry data is copied as files to the SSTL mission operations center or partner groundstations via an S-band downlink providing an 8.1Mbps serial stream.

8.1Mbps was chosen because it is the maximum rate supported by the serial interface on the Cisco routers used in the ground stations; this was adopted as the rate at which onboard payloads communicate with the ground station and the onboard router.

There is also a low-rate 38.4kbps downlink to provide satellite status telemetry when the high-rate downlink is not active. Commands are received and software is uploaded via a low-rate uplink at 9600bps [fig. 4].

All of these links carry IP packets inside standard 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 and an earlier Cisco router in the Surrey ground station.[3] Without that previous work, done in cooperation with NASA Goddard's OMNI project, to lay down use of commercial networking standards by SSTL's satellite and ground station network, integration of a commercial router into the satellite would have been far more difficult.

Payloads are given access to the downlink according to an uploaded schedule planning future events, and it is desirable to 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 *Saratoga*, a custom rate-based UDP-based file transfer protocol designed and implemented by SSTL.[19] This protocol has a far higher transfer rate than TCP's design permits. Its implementation has a smaller code footprint size and faster performance than an earlier onboard implementation of the CCSDS File Delivery Protocol (CFDP) that was written by SSTL and first used onboard AlSAT-1. Use of Saratoga has increased the amount of image data that can be transferred during a pass, so that the entire contents of an SSDR's memory can be downloaded, and that SSDR can then be turned off until its next use, in order to conserve energy.

The on-board computer (OBC) that controls the UK-DMC platform can provide telemetry about the status of the satellite as a UDP broadcast stream from its IP stack. This telemetry stream is sent in-band down any available high-rate or low-rate downlink. An SSDR can repeat frames received from the OBC onto a high-rate link in software to enable this. The term 'OBC' dates from a time when there was only one computer onboard SSTL satellites.

The ground stations belonging to SSTL and to the partner countries owning other satellites in the Disaster Monitoring Consortium are networked together using the Internet. PCs on each ground station's Ethernet local area network (LAN) run applications for dealing with satellite telemetry and images.

7. SSTL's 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 each MPS to:

1. receive and collate imaging requests for areas of user interest;
2. perform orbit propagation and calculate satellite passes providing image acquisition opportunities;

3. schedule and prioritize acquisition opportunities based on user 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 independent 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, the existing 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. This used widely-adopted network standards: XML-RPC (remote procedure calls) and SOAP.

Live interaction between these systems was demonstrated successfully, with the MPS at SSTL's ground station in Guildford executing and delivering on VMOC image requests during and after testing and demonstrations at Vandenberg Air Force Base. The VMOC was allocated an appropriate priority so as not to interrupt established imaging commitments.

8. Virtual Mission Operations Center

The General Dynamics (GD) 'Nautilus Horizon' VMOC 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 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. 5].

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 functions of the GD VMOC include:

1. enabling system operators and data users to be remote from ground stations;
2. verifying individual users and their authorizations;
3. establishing a secure user session with the platform;
4. performing user and command prioritization and contention control; the 'Nautilus' name reflects the multiple levels of tiered security implemented;
5. applying mission rules and performing command appropriateness tests.
6. relaying data directly to the remote user, without human intervention;
7. providing a knowledge database, with the capabilities to enable interaction with other, similar, systems;
8. providing an encrypted gateway for access by "unsophisticated" remote users of sensor data.

9. Testing CLEO with VMOC

The CLEO project, funded by Cisco Systems, and the VMOC project, funded by the RAI-NC program, are entirely separate, but are complementary in their shared use of the Internet Protocol.

The overlapping organizational groups involved in these projects gained mutual benefit from working together, as their work was already compatible technically, due to their shared use of common open standards.

The VMOC and router testing conducted at Vandenberg Air Force Base was a collaborative experiment centered on the Air Force, the Army and NASA Glenn Research Center, and involving many organizations, including Cisco Systems and SSTL.

NASA Glenn worked with Cisco to test the CLEO router under a mutually beneficial US Space Act agreement. The Army and Air Force Space Battlelabs provided support, and performed their overall metrics collection and evaluation of the utility of VMOC for commanding space-based assets, as part of the OSD-sponsored VMOC effort.

The VMOC evaluation occurred 'in the field' during 1-13 June 2004, followed by a three-day live demonstration during 14-16 June. The Army Space Support Element Toolset was deployed at the Vandenberg site. Operators specified areas of the Earth, received satellite images and telemetry, and commanded the router [fig. 6].

VMOC users in the field relied on mobile networking 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 in Guildford [fig. 7].

Both the CLEO router and the IP-based VMOC software application were able to rely 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 active nodes on a large IP-based network that seamlessly merged space and ground assets.

The capabilities demonstrated here emerge from the cooperation of all parts, and from the whole created from those parts being greater than the sum of the individual parts.

These desirable outcomes resulted from shared adoption of the Internet Protocol enabling full technical collaboration and interaction.

The success of this demonstration was *not* due to careful top-down long-term planning of a single integrated system that would meet agreed goals, but due to confidence that interoperability of independent capabilities based around common standards would itself lead to success.

10. Use of mobile networking

SSTL's existing merged space-ground architecture was designed around a single ground station local area network as a flat IPv4 network. All assets, both space- and ground-based, appear to reside on the ground station network.

All assets in each separate DMC ground station use the same private address space. It is necessary for the common addresses used by each ground station to be manually mapped to globally unique addresses, using Network Address Translation (NAT), in order to be accessed from the Internet. Predictive routing — knowing when a satellite will be visible over a ground station, and thus which spacecraft payloads are available and which addresses are in use — is used for remote access to the space-based part of the network.

Mobile networking, which shields an entire local area network from address changes using Mobile IP,[20] was deployed with CLEO to demonstrate a simplified method of direct access to space-based assets. Mobile networking makes it relatively easy to share network resources and roam between different IP networks, i.e. one does not have to administer the entire ground station network the spacecraft's network connects to, or alter its address space or routing.

As CLEO is a secondary, experimental, payload, support for mobile networking had to be added without disrupting either SSTL's existing network operations or the primary imaging mission.

Use of mobile networking provides CLEO with a permanent, static, public IP address that the VMOC can use to command the spaceborne router, separate from the ground station currently visible to the satellite.

The CLEO router registers with the mobile networking Home Agent at NASA Glenn's headquarters in Cleveland, Ohio, and can be accessed indirectly via the Home Agent or directly during a pass over a ground station.

CLEO has been controlled via both SSTL's own ground station in Guildford, England, and the Universal Space Network (USN) station near Poker Flat, Alaska, which duplicates the modem use by SSTL.

11. Some problems during operations

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

'Pass-through' bridging software, needed for frames from the router to reach the ground as the router is not directly connected to the satellite's wireless links, was written and then uploaded to the PowerPC SSDRs after launch. Before this software was uploaded, the onboard router was only reachable and shown to work with console access via the OBC.

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.

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 bridging 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. SSTL's soft scheduling methodology makes rescheduling future events by updating an uploaded list of tasks to be carried out relatively straightforward.

Soft configuration of CLEO could take advantage of latent capabilities of the IOS router software whose use had not been anticipated earlier. For example, the onboard topology for the router is such that when pass-through mode is active, the OBC and router effectively share the serial interface and address at the end of the uplink. When both devices are active, only one should respond to packets 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 would respond on the shared interface. Testing this configuration change on the ground-based testbed and then repeating the commands on orbit during a pass was simpler than recompiling and uploading the OBC software would have been.

The OBC IP stack is written in-house by SSTL and its implementation on the UK-DMC satellite was considered experimental; the OBC can also run third-party AX.25-based communications software (and the other DMC satellites have also done so, while their payload SSDR computers are IP-based and use Saratoga). This AX.25 fallback use reflects SSTL's long amateur radio experience and heritage. Only one of the AX.25 and IP/Frame Relay operating systems is run onboard the UK-DMC OBC at a time. These do share common HDLC framing.

The later Chinese Beijing-1 satellite is IP-only, as is its OBC, and also has an X-band downlink to support an extra high-resolution camera. This downlink carries HDLC framing at either 20 or 40 Mbps to a High Speed Serial Interface (HSSI) on a Cisco 7204VXR router in the ground station, following Hogie *et al.*[3]

SSTL has moved the UK-DMC OBC back to AX.25 while debugging its internal software, which removed a source of UDP-based telemetry during passes.

While returned to AX.25 use for communication, the OBC is powered down during high-rate passes to avoid inadvertently responding to IP traffic that it would misinterpret as AX.25 frames. This prevents multiplexing of payload data with in-band telemetry from the OBC. (Cisco routers automatically discard frames that don't match specified Frame Relay headers; this and the shared use of HDLC makes it easy for the Cisco 2621 router to coexist with AX.25 equipment in each ground station.)

It may be useful to also carry AX.25 frames within Frame Relay, to permit different types of traffic to be clearly identified separately by Frame Relay as outlined by Hogie *et al.*,[3] so that they can coexist within the same shared infrastructure.

The Universal Space Network Alaska ground station that was used to receive low-rate telemetry during the Vandenberg demonstration took some time to make fully operational.

It was discovered that the high-speed downlink signal was too strong for and saturated the Alaskan ground station's 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 addressed in further ground station work.

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 General Dynamics 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 for and between 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 more functionality off to the autonomous SSTL MPS, moving away from hard absolute commanding by VMOC to a higher-level softer request negotiation model.

Despite these minor problems with its surrounding infrastructure, the CLEO onboard router itself performed entirely as intended.

12. Further networking demonstrations

Other demonstrations of CLEO and VMOC have been held, using as little as a laptop PC, a web browser, and Internet connectivity.

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. Further demonstrations took place on 18 November 2004 to the leadership of Air Force Space Command during its Commanders' Conference in Los Angeles, California.

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

Access to CLEO using secure web access via VMOC and the Alaska ground station was shown during the IEEE Milcom conference exhibition, from 18-20 October 2005.[21]

13. Moving GPS reflectometry data

CLEO interconnects the PowerPC SSDRs with the slower StrongArm SSDR controlling the onboard GPS reflectometry experiment[18] [fig. 4]. If CLEO was not present, the SSDRs would be interconnected by a redundant mesh of links. As CLEO uses those connections, CLEO acts as a 'powered wire' to allow the StrongArm SSDR to talk to its peers.

The StrongArm-based SSDR is only fast enough to output frames at a maximum of around 3 Mbps. CLEO forwards data from it to a PowerPC SSDR, from where the data can be downloaded more rapidly with higher wireless link utilization. The StrongArm-based SSDR is then turned off to conserve energy. A reflectometry data transfer now forms a small part of an image data transfer pass, rather than needing a dedicated pass.

The normal operation for transferring GPS reflectometry data to ground now involves scheduling turning on CLEO for a period of up to half an hour before a pass, to transfer all data through CLEO to a faster SSDR. CLEO and the StrongArm-based SSDR are then powered down before the pass. This uses autonomous onboard networking to show that CLEO remains operational. This technique has been carried out over thirty times.

14. Lessons from tests and operations

An Internet router is good for arbitrating fairly between nodes and traffic 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 owning and managing all computers onboard a small satellite, and with the power budget and accessibility concerns of a small satellite, a coarser-grained scheduling paradigm becomes much more attractive. Data files are downloaded from an onboard payload, before switching attention and link capacity to the next payload. Once a data recorder holds nothing more of interest, it is simply turned off until it is next needed.

On the DMC satellites, each computer is scheduled with the aim of giving it dedicated access to the downlink. Multiplexing of frames sent from other payloads, such as the low-rate telemetry generated by an IP-based OBC, can also be carried out in software by the computer driving the downlink. Although scheduling of payload events is timetabled in advance using ground station pass schedules, a ‘soft scheduling’ model is used where the schedule is uploaded as a textfile to the platform’s onboard computer to interpret and follow. The schedule for future events can be updated, altered and uploaded during any pass before the events take place.

Pass utilization — getting as much as possible from each pass over a ground station during the limited available download time — dominates the operating model for a low-Earth-orbiting small satellite doing store-and-forward download. Pass utilization depends on link utilization. (This assumes that the satellite does not have connectivity through a large-area geostationary transponder that could relay image data as it is recorded.)

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 on-demand audio and video streaming, as well as remote connectivity via secure shell (ssh). For a remote-sensing satellite whose images require heavy computation to be processed and adjusted, immediate end-to-end delivery of payload data is less important.

End-to-end path utilization in the end-to-end Internet model is lower than local link utilization, and is dominated by Internet congestion caused by competition. This competition-oriented terrestrial Internet mode of operation would be more attractive for autonomous payloads on large shared platforms, e.g. the International Space Station or the Hubble telescope, or for payloads onboard, interconnecting, or communicating via always-accessible geostationary satellites using shared high-bandwidth links.

The high asymmetry in the ratio of forward downlink/back uplink link capacity for the DMC satellites lies beyond the 50:1 ratio that is considered a necessary minimum so that congestion of TCP acknowledgments on the back path does not limit TCP throughput on the forward path. Along with TCP’s slow-start and congestion control algorithms, this prevents TCP from effectively utilizing a dedicated link.

The desire to increase link and pass utilization and download as much imaging data as possible led to replacing a network stack implementing CFDP that was considered large, slow and resource-hungry. A custom network stack using a rate-based UDP transfer protocol, Saratoga, was developed by SSTL in order to fill the downlink with image files and use the limited time of up to twelve minutes in a pass as effectively as possible.[19]

The images are downloaded from the satellite across a single link, the downlink, to a ground station, and no further. Saratoga’s simple rate-based design deliberately lacks congestion control algorithms, making it unsuitable for widespread Internet use between any endhosts.

Although TCP has congestion control and is suitable for Internet use, TCP cannot be engineered to make efficient use of the downlink during available limited pass times; TCP’s slow start, probing the limits of link capacity and backing off, are suboptimal for link use dedicated to a single user. TCP would be more effective for arbitrating access between multiple competing onboard computers, owned by different operators, which use a multiplexing model of operation rather than the overall shared scheduling model outlined here.

Low-rate in-band telemetry frames from the OBC, when copied over and multiplexed via ‘passthrough’ software on an SSDR, are hardly competition to a Saratoga image transfer from that SSDR that fills the majority of the 8.1Mbps downlink.

The image download model here is more analogous to e.g. application-level http proxy caching, where files are cached locally to avoid creating long, bottleneck-constrained, paths. Images can be processed at the ground station cache, and then fetched on demand by terrestrial users. However, the end-to-end connectivity model can still be used for:

1. 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 from the source. Telemetry streams can have unreliable delivery; if a packet describing the status of the satellite is lost, there will be another one describing much the same status along very soon.
2. real-time commanding, done by uploading small scheduling files, and for direct access to the onboard router;

A LEO imaging satellite could use a geostationary transponder to download imaging data to ground stations for longer periods. This has been done via the European Artemis satellite, which uses a Ka-band transponder to relay data from the Envisat satellite,[22] and uses the SILEX (semiconductor laser intersatellite-link experiment) payload to receive data from SPOT-4.[23]

Even when downloading via a geostationary satellite, power and link utilization efficiency concerns, the desire to switch between scheduled payloads based upon need, and TCP's well-documented inefficiencies in adjusting to geostationary delays and high bandwidth-delay products would encourage the LEO satellite to adopt rate-based transfer protocols and scheduled use rather than TCP and competing use.

Adoption of terrestrial network technologies means necessary adoption of widespread terrestrial security paradigms, which are fortunately well-understood. SSTL's ground station LAN becomes a part of SSTL's corporate network, and is 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 desirable, but has not been done. Later SSTL missions are implementing link encryption.

15. Further developments with VMOC

Development of General Dynamics' VMOC software has continued to enhance system interoperability and responsiveness, increase situational awareness, and support automated machine-to-machine interactions.

An enhanced VMOC, providing increased Application Programming Interface (API) functionality, has been prepared to support the Air Force Space Battlelab's SAFE (Space Apportionment For Effect) demonstration. A Space Apportionment VMOC can be used to model conflicting mission requirements and prioritize multiple user accesses to the Mission VMOCs tied to the space platforms.This "system of systems" approach allows for centralized control with decentralized execution within a net-centric environment.

16. 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 has relied 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 normal operations and from the primary imaging mission. Up to several passes per week have been used to access and test the CLEO router.

The CLEO router remains operational after over three full years in space. CLEO has been used in orbit for over twenty-seven months, and has been turned on more than seventy-five times for use during passes over ground stations and for reflectometry data transfer. CLEO has had more than fifteen hours total active use on orbit.

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. As a terrestrial product, CLEO is not instrumented to measure space radiation events or cumulative dosage. No anomalies attributable to single-event upsets caused by radiation have been noticed. CLEO is only turned on for use for ground passes of twelve minutes at a time, or for reflectometry data transfers and testing for up to just over half an hour, severely limiting its operational radiation exposure. Commercial laptops operated in manned environments in lower orbits on Mir and the space shuttle have encountered upsets after hours of use, as have autopilots on commercial jet planes.[24]

Although CLEO was launched with IPv6 and IPsec functionality onboard in its firmware, and the Cisco routers and firewalls used in each DMC groundstation support IPsec and are capable of running IPv6, IPv6 was yet to be enabled in space as we write. The existing network infrastructure at SSTL relies on IPv4, although this can be upgraded to use IPv6 as well. Testing IPv6 and IPsec with CLEO has already been examined in detail via the ground-based testbed.

CLEO's success in using IOS router software in orbit has led to Cisco Systems porting its IOS software to run on a space-qualified, radiation-hardened, processor in the PowerPC family.[25] This is a step towards a hardened embedded router which could be tested in geostationary orbit, or which could be flown in high-altitude applications demanding reliability. The hardware and interfaces of such embedded routing functionality would be very different from that of either this porting experiment or the CLEO demonstrator.

17. Further developments for satellites

With use of onboard processing and switching of frames and packets, we envisage onboard payloads being interconnected by smarter satellite buses, where the platform provides a network-level communications bus as well as power and housekeeping. What such a bus will be is an open question, with a number of different approaches currently being pursued by a number of organizations.

Elon Musk's SpaceX has adopted Ethernet as the bus onboard its rocket designs. This could influence the bus designs of satellites launched by those rockets, and how satellites and payloads are activated after launch.[26]

Payloads that have different owners and operators should be able to communicate with other payloads onboard the same satellite to increase their overall system-level flexibility.

With links between payloads on satellites that already have uplinks and downlinks for communications, switching decisions on where to send data clearly have to be made. Each satellite becomes a network (and, with intersatellite links, part of a larger network), and the boundaries between network Autonomous Systems can lie between payloads and within the satellite itself.

An initial unambitious step in the evolution of satellites towards a fuller networking role is to just stop thinking of a single satellite transponder's 'link budget' and to start talking of the separate 'uplink budget' and 'downlink budget'. Digital signal processing is just one form of onboard processing. Onboard processing can be incrementally extended in order to support frame and packet processing, which can then be leveraged to enable useful interconnections between onboard payloads.

Conclusions

The CLEO experiment onboard the UK-DMC satellite has shown that a commercial off-the-shelf router can be adapted to and be used in the space environment in low Earth orbit.

CLEO has demonstrated onboard IP networking and has shown that mobile networking can be used for communications across disparate and separate networks via 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 used to create a successful operational service.

The Disaster Monitoring Constellation of small satellites shows that IP-based data delivery of remote sensing image files from orbit can 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 upon open standards based around IP to manage complex applications involving satellites.

Acknowledgments

We greatly appreciate the combined, coordinated and continuing efforts and the ongoing cooperation of the many collaborating commercial, civil and military participants throughout the creation and operation of CLEO, and its integration with

VMOC, testing and demonstrations. A list of participants in the test campaign is given in the NASA technical memorandum that describes testing CLEO and VMOC.[27]

References

1. C. Underwood, S. Machin, P. Stephens, D. Hodgson, A. da Silva Curiel and M. Sweeting, Evaluation of the Utility of the Disaster Monitoring Constellation in Support of Earth Observation Applications, paper IAA-B5-1501, 5th IAA Symposium on Small Satellites for Earth Observation, Berlin, Germany, April 2005.
2. B. Conner, L. Dikeman, V. Osweiler, S. Groves, D. Schoenfelt, P. Paulsen, W. Ivancic, E. Miller and J. Walke, Bringing Space Capabilities to the Warfighter: Virtual Mission Operations Center (VMOC), paper SSC04-II-7, 18th AIAA/USU Conference on Small Satellites, Logan, Utah, August 2004.
3. K. Hogie, E. Criscuolo, and R. Parise, Using Standard Internet Protocols and Applications in Space, Computer Networks, special issue on Interplanetary Internet, vol. 47 no. 5, pp. 603-650, April 2005.
4. V. G. Cerf, Packet satellite technology reference sources, Internet Engineering Task Force RFC 829, DARPA, November 1982.
5. K. Seo, J. Crowcroft, P. Spilling, J. Laws and J. Leddy, Distributed Testing and Measurement across the Atlantic Packet Satellite Network (SATNET), SIGCOMM ’88, Palo Alto, California, August 1988.
6. R. Blott, and N. Wells, The Space Technology Research Vehicles: STRV-1a, b, c and d, 10th AIAA/USU Conference on Small Satellites, Logan, Utah, September 1996.
7. C. Jackson, C. Smithies and M. Sweeting, NASA IP demonstration in-orbit via UoSAT-12 minisatellite, 52nd International Astronautical Congress, Toulouse, France, October 2001.
8. A. da Silva Curiel, L. Boland, and J. Cooksley, *et al.*, First results from the Disaster Monitoring Constellation (DMC), paper IAA-B4-1302, 4th IAA Symposium on Small Satellites for Earth Observation, Berlin, Germany, April 2003.
9. K. Rubio, J. Janicik, and J. Szielenski, CHIPSat’s TCP/IP mission operations architecture — elegantly simple, paper SSC02–IV–4, 16th AIAA/USU Conference on Small Satellites, Logan, Utah, August 2002.
10. Cisco Systems, The first 90,000 miles are toll-free, company profile, Cisco Systems, September 2002.
11. W. Jackson, Astronauts call home via shuttle VoIP link, Government Computing News, vol. 20 no. 5, 5 March 2001.
12. W. Ivancic, T. Bell, and D. Shell, ISS and STS commercial off-the-shelf router testing, NASA Technical Memorandum TM-2002-21130, April 2002.
13. L. Wood, A. da Silva Curiel, J. Anzalchi, D. Cooke and C. Jackson, Slot clouds: getting more from orbital slots with networking, paper IAC-03-U.4.07, 54th International Astronautical Congress, Bremen, Germany, September 2003.
14. D. Floreani and L. Wood, Internet to orbit, Cisco Systems Packet Magazine, vol. 17 no. 3, pp. 19-23, third quarter 2005.
15. D. Cooke, R. Lancaster, and J. Buckley, Cisco router 3200 UK-DMC payload interface control, SSTL internal technical document, May 2003.
16 Hughes Electronics Corporation, Launches of Hughes HS 601 satellites ready to resume, press release, Hughes Electronics Corporation, 11 August 1998.
17. D. Hodgson, L. Boland, S. Mackin, P. Palmer, Y. Hashida, N. Bean, A. Brewer, H. Kadhem, C. Jackson, P. Davies, A. da Silva Curiel and M. Sweeting, Earth Observation Constellations with Automated Image Delivery, paper IAC-04-IAA.4.11.1.05, 55th International Astronautical Congress, Vancouver, Canada, October 2004.
18. S. Gleason, S. Hodgart, S. Yiping, C. Gommenginger, S. Mackin, M. Adjrad and M. Unwin, Detection and Processing of bistatically reflected GPS signals from low Earth orbit for the purpose of ocean remote sensing, IEEE Transactions on Geoscience and Remote Sensing, Vol. 43, No. 6, pp. 1229-1241, June 2005.
19. C. Jackson, Saratoga file transfer protocol, SSTL internal specification, May 2004.
20. C. Perkins, ed., IP Mobility Support for IPv4, Internet Engineering Task Force RFC 3344, August 2002.
21. L. Wood, D. Shell, W. Ivancic, B. Conner, E. Miller, D. Stewart and D. Hodgson, CLEO and VMOC: enabling warfighters to task space payloads, unclassified track, IEEE MILCOM 2005, Atlantic City, New Jersey, October 2005.
22. P. A. Dubcock, F. Spoto, J. Simpson, D. Spencer, E. Schutte and H. Sontag, The

Envisat satellite and its integration, ESA Bulletin no. 106, June 2001, pp. 26-45.

23. T. Tolker-Nielsen and G. Oppenhauser, In-orbit test result of an operational optical intersatellite link between ARTEMIS and SPOT-4, Free-Space Laser Communication Technologies XIV, Proceedings of SPIE, vol. 4635, April 2002, pp. 1-15.
24. C. Dyer, Radiation Effects on Spacecraft and Aircraft, Space Weather Workshop, ESTEC, Netherlands, December 2001.
25. D. Buster, Towards IP for space based communications systems; a Cisco Systems assessment of a single board router, unclassified track, IEEE MILCOM 2005, Atlantic City, New Jersey, October 2005.
26. Payload User's Guide – Falcon Launch Vehicle, SpaceX specification, p. 12, 2nd revision, October 2004.
27. W. Ivancic, P. Paulsen, D. Stewart, D. Shell, L. Wood, C. Jackson, D. Hodgson, J. Northam, N. Bean, E. Miller, M. Graves and L. Kurisaki, Secure, network-centric operations of a space-based asset: Cisco router in Low Earth Orbit (CLEO) and Virtual Mission Operations Center (VMOC), NASA Technical Memorandum TM-2005-213556, May 2005.

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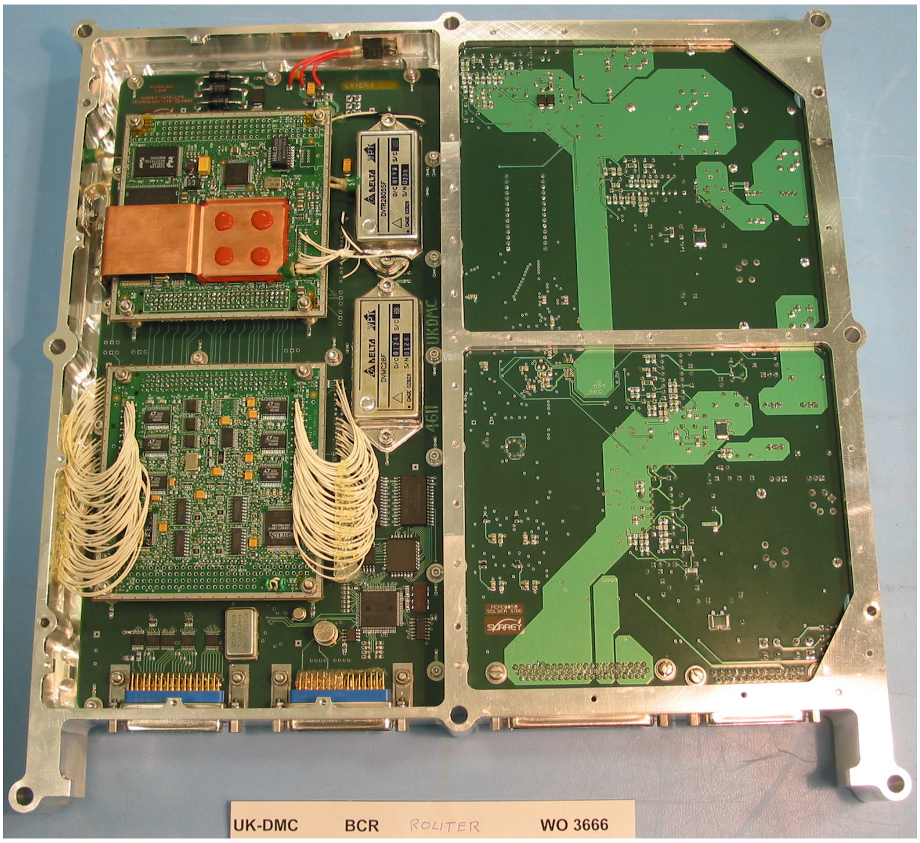
Scott Lynch (lynch@uspacenet.com) is a Systems Engineer for Universal Space Network, Inc. He previously gained a decade of experience of Electronic Warfare Systems with the US Navy. Scott began working with IP technology for commercial ground station implementation with the CHIPSat mission in 2003, and has continued this with NASA Goddard and Glenn for the UK-DMC satellite. Scott and the Universal Space Network engineering team are working to implement IP satellite communications across the Universal Space Network ground network in support of further IP-enabled missions.

Chris Jackson (c.jackson@sstl.co.uk) is a principal engineer responsible for ground systems and operations at Surrey Satellite Technology Ltd. Chris has worked at SSTL for over twelve years, where he has been involved with flight and ground software systems, space-to-ground protocols and flight operations for over twenty space missions.

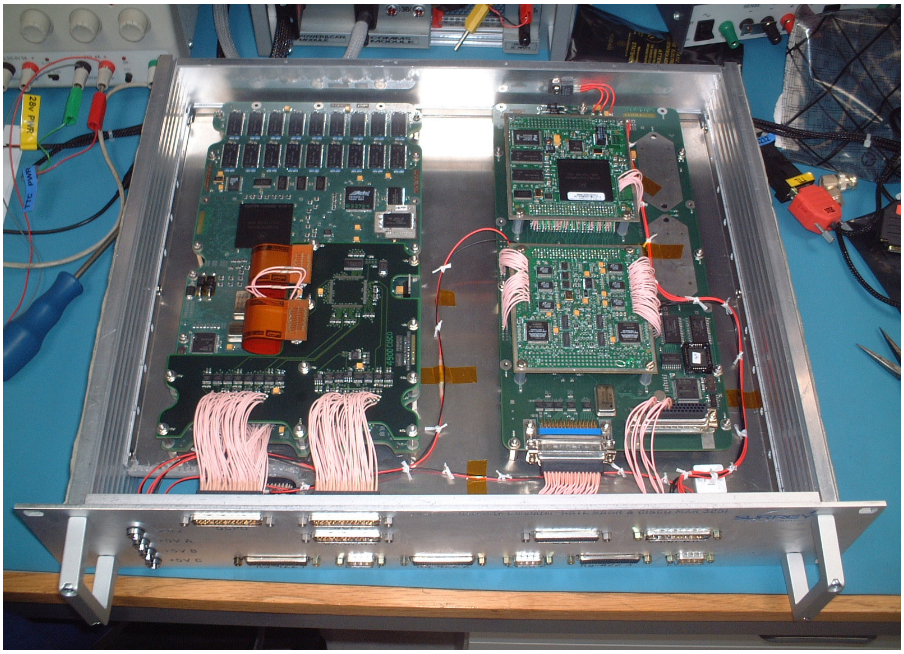
Alex da Silva Curiel (a.da-silva-curiel@sstl.co.uk) is the technical director for the Surrey Satellite Technology Ltd group, where he has been involved in more than twenty small satellite missions in a variety of engineering and management roles. He is a member of the ESA/CNES Small Satellite Systems and Services technical committee, a member of the IAF small satellite technical committee, and the UK lead for the ISO working group on Satellite Operations and Ground systems. Alex holds a masters degree in satellite engineering from the University of Surrey, and has published more than fifty papers on aspects of satellite communications and mission design.

David Cooke (d.cooke@sstl.co.uk) is a senior design engineer at Surrey Satellite Technology Ltd, where he designs onboard data-handling architectures and subsystem modules. Dave holds a BEng degree in electronic engineering.



back left: router card with heatsink brace. right: UK-DMC battery charge regulator
front left: serial card interfaced to payloads via half-width motherboard.

Figure 2: CLEO assembly in payload tray



left: SSDR assembly. right: router assembly.

Figure 3: Ground-based testbed

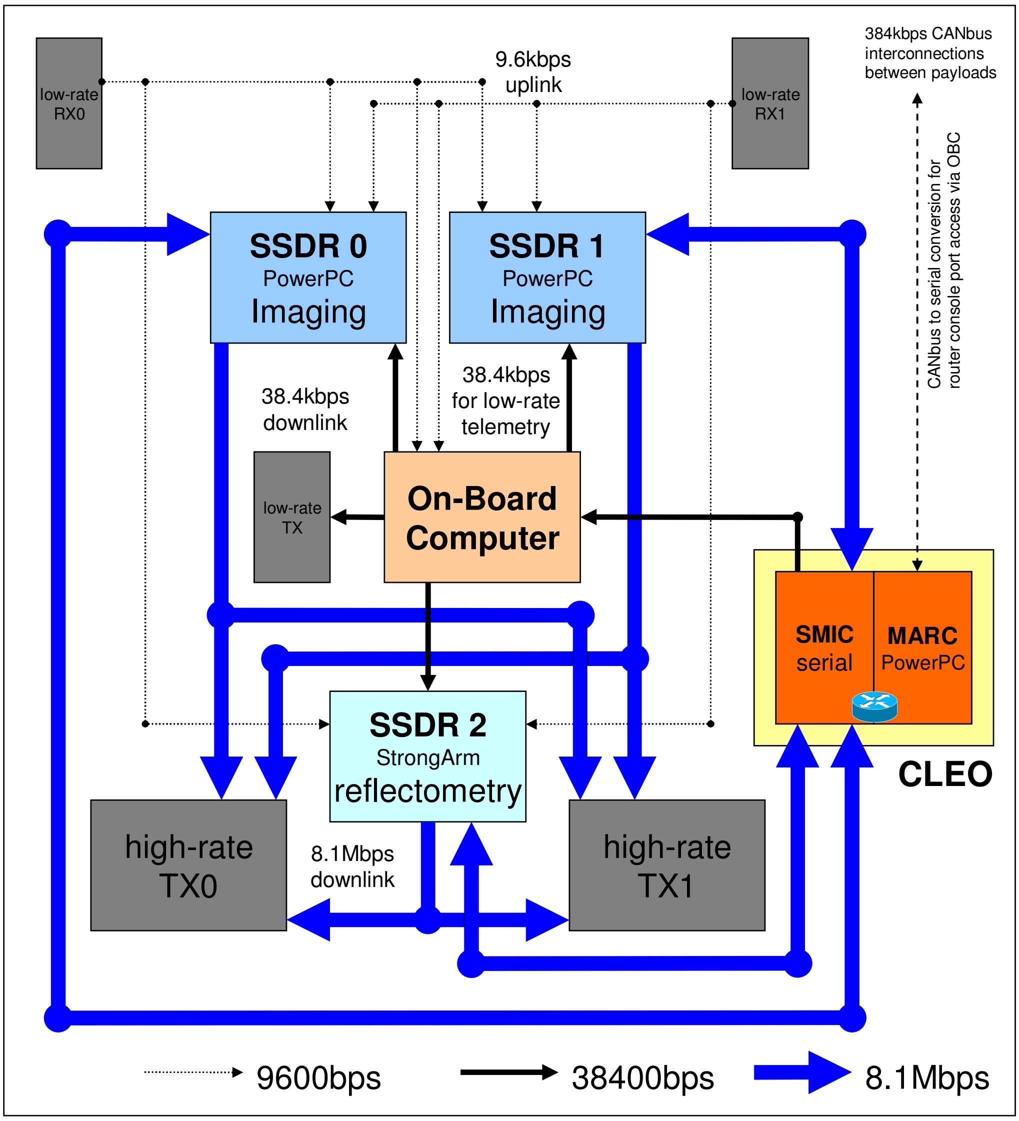


Figure 4: Logical connectivity of the UK-DMC satellite's internal onboard network

Dan Shell (dshellwireless@gmail.com) is a network architect active in IP mobility consulting and research. He is currently the primary investigator for a Congressionally-funded research project using aerostats and IP mobility. In twelve years at Cisco Systems, Dan was a Technical Leader in the Government Services Unit, where he led development of mobile networking and drove development of Cisco's mobile access router. Dan was active in IP over satellite research with NASA Glenn Research Center as part of Cisco's Space Act agreement with NASA, and supported other US federal agencies in deploying network solutions.

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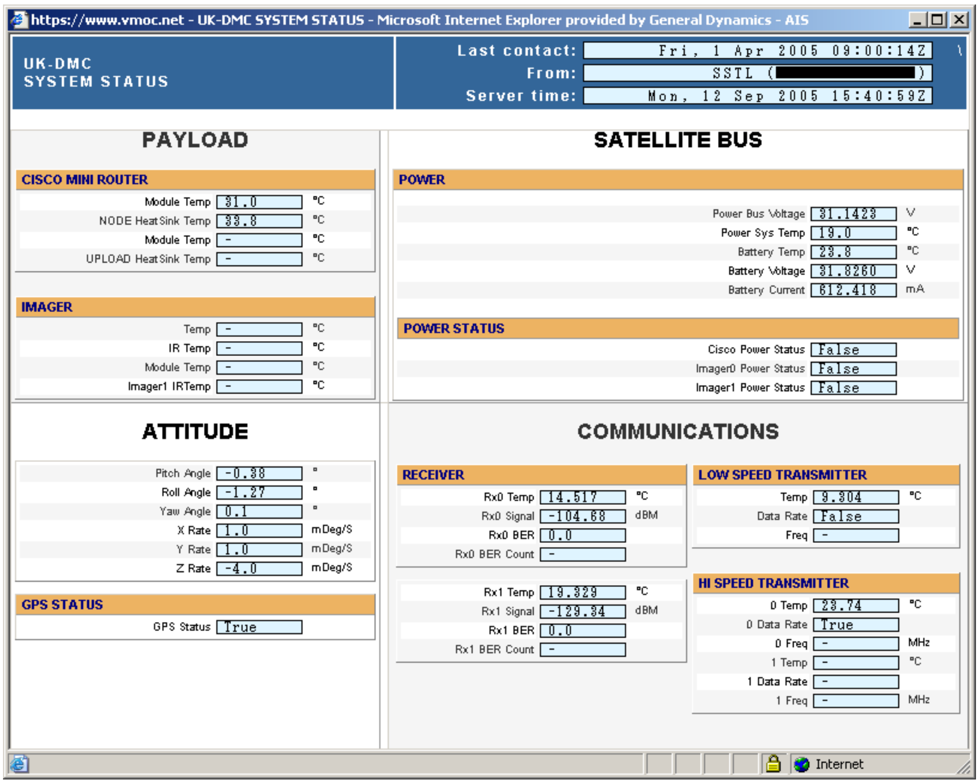


https://www.vmoc.net - UK-DMC SYSTEM STATUS - Microsoft Internet Explorer provided by General Dynamics - AIS

UK-DMC
SYSTEM STATUS

Last contact: Fri, 1 Apr 2005 09:00:14Z
From: SSTL ([redacted])
Server time: Mon, 12 Sep 2005 15:40:59Z

PAYLOAD

CISCO MINI ROUTER

Module Temp	31.0	°C
NODE Heat Sink Temp	33.8	°C
Module Temp	-	°C
UPLOAD Heat Sink Temp	-	°C

IMAGER

Temp	-	°C
IR Temp	-	°C
Module Temp	-	°C
Imager1 IRTemp	-	°C

SATELLITE BUS

POWER

Power Bus Voltage	31.1423	V
Power Sys Temp	19.0	°C
Battery Temp	23.8	°C
Battery Voltage	31.8260	V
Battery Current	612.418	mA

POWER STATUS

Cisco Power Status	False
Imager0 Power Status	False
Imager1 Power Status	False

ATTITUDE

Pitch Angle	-0.38	°
Roll Angle	-1.27	°
Yaw Angle	0.1	°
X Rate	1.0	mDeg/S
Y Rate	1.0	mDeg/S
Z Rate	-4.0	mDeg/S

GPS STATUS

GPS Status	True

COMMUNICATIONS

RECEIVER

Rx0 Temp	14.517	°C
Rx0 Signal	-104.68	dBM
Rx0 BER	0.0	
Rx0 BER Count	-	
Rx1 Temp	19.329	°C
Rx1 Signal	-129.34	dBM
Rx1 BER	0.0	
Rx1 BER Count	-	

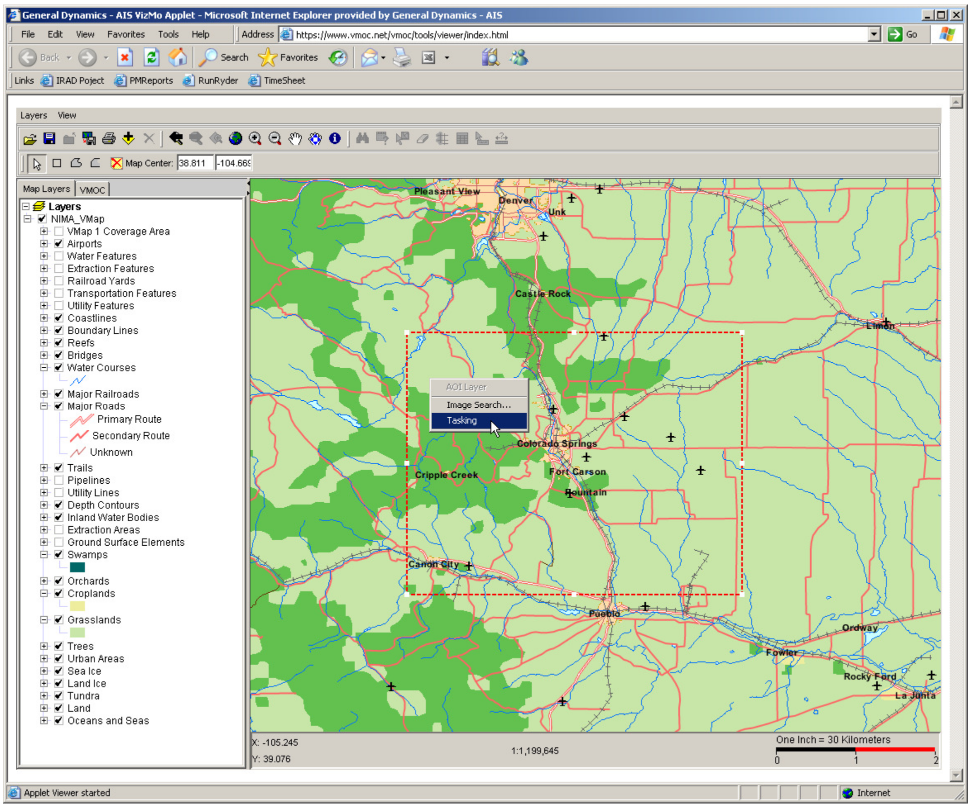
LOW SPEED TRANSMITTER

Temp	9.304	°C
Data Rate	False	
Freq	-	

HI SPEED TRANSMITTER

0 Temp	23.74	°C
0 Data Rate	True	
0 Freq	-	MHz
1 Temp	-	°C
1 Data Rate	-	
1 Freq	-	MHz

a. Live UK-DMC telemetry relayed from ground stations during passes and recorded.



General Dynamics - AIS VizMo Applet - Microsoft Internet Explorer provided by General Dynamics - AIS

Address: https://www.vmoc.net/vmoc/tools/viewer/index.html

Map Center: 38.811 -104.66

Layers
- ☑ NIMA_VMap
  - ☐ VMap 1 Coverage Area
  - ☑ Airports
  - ☐ Water Features
  - ☐ Extraction Features
  - ☐ Railroad Yards
  - ☐ Transportation Features
  - ☐ Utility Features
  - ☑ Coastlines
  - ☑ Boundary Lines
  - ☑ Reefs
  - ☑ Bridges
  - ☑ Water Courses
  - ☑ Major Railroads
  - ☑ Major Roads
    - Primary Route
    - Secondary Route
    - Unknown
  - ☑ Trails
  - ☐ Pipelines
  - ☐ Utility Lines
  - ☑ Depth Contours
  - ☑ Inland Water Bodies
  - ☐ Extraction Areas
  - ☐ Ground Surface Elements
  - ☑ Swamps
  - ☑ Orchards
  - ☑ Croplands
  - ☑ Grasslands
  - ☑ Trees
  - ☑ Urban Areas
  - ☑ Sea Ice
  - ☑ Land Ice
  - ☑ Tundra
  - ☑ Land
  - ☑ Oceans and Seas

X: -105.245
Y: 39.076

1:1,199,645

One Inch = 30 Kilometers

Applet Viewer started

b. Graphical area selection and tasking interface.

Figure 5: Screenshots of the VMOC client web browser user interface

Figure 6: Space Support Element deployed ‘in the field’ at Vandenberg Air Force Base

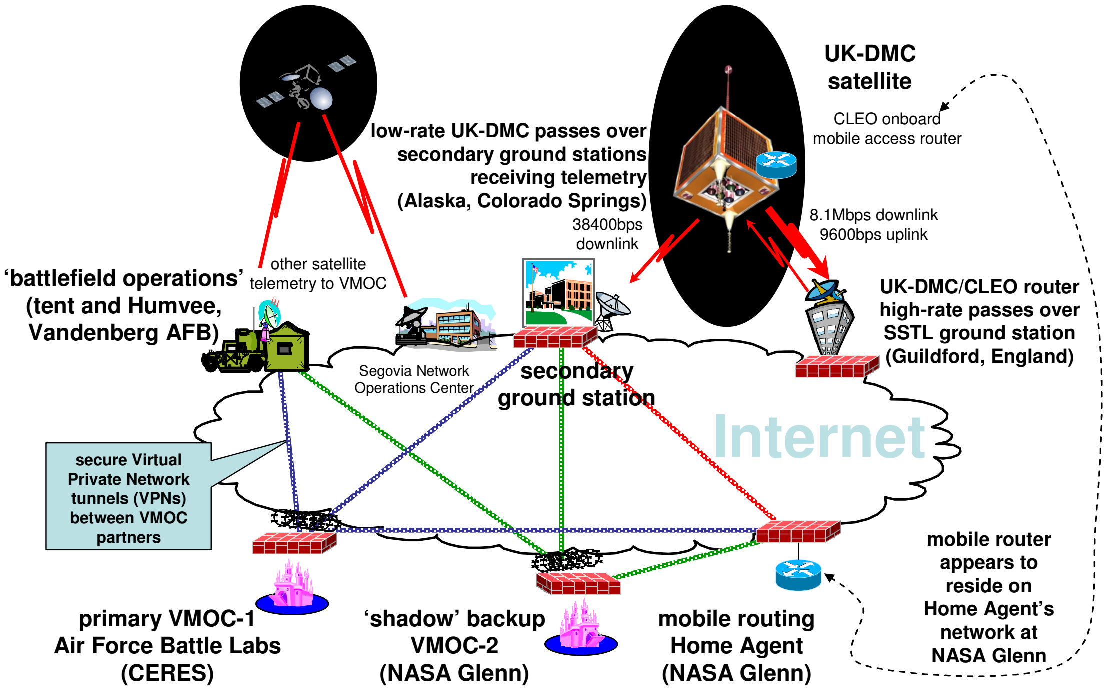


Figure 7: Network topology for the Vandenberg demonstration