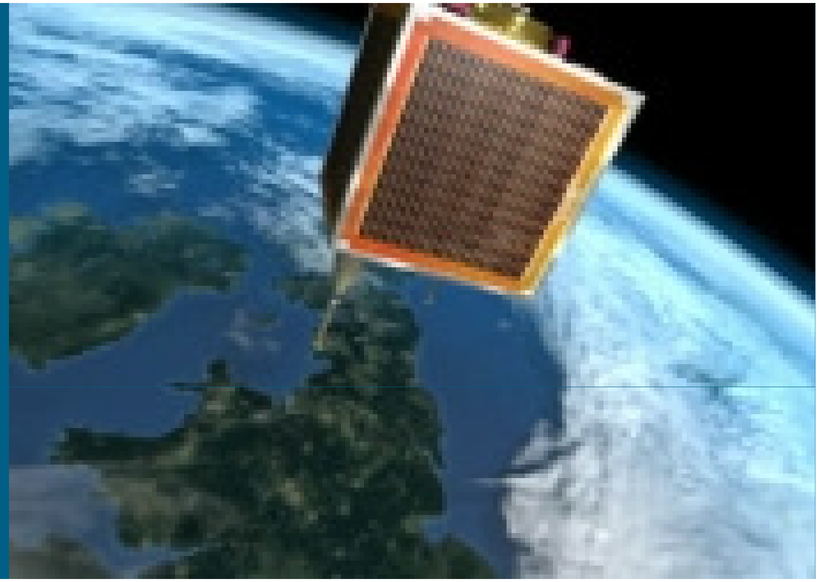
CLEO
Cisco router in Low Earth Orbit

Cisco Systems space team



Lloyd Wood

A space vision from a networking company

One day, each and every manned and unmanned spacecraft, high altitude platform, unmanned aerial vehicle, airframe... will be a node on the network.

Terrestrial and space communications will be indistinguishable.

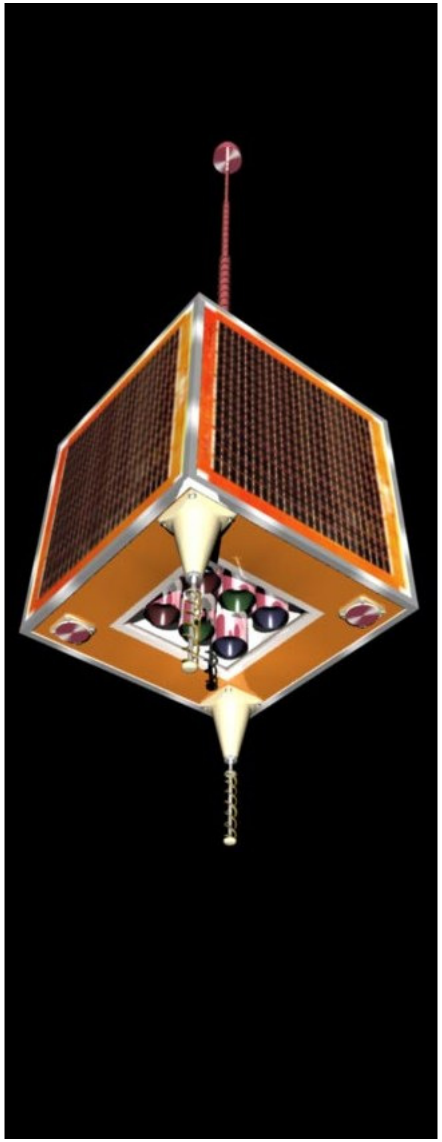
(We talk about merged space-ground architectures.)

Wired has realized where we could go…

Found – Artifacts from the future, Mark McCluskey, *Wired* TEST, US special supplement, p. 160, in print October 2006.

Executive summary

- UK-DMC satellite, with Cisco router onboard, launched with other satellites into low Earth orbit, September 2003.
- UK-DMC and sister satellites are based around use of Internet Protocol (IP). IP works for satellite and payload communication and control.
- IP internetworking of satellite and router tested and validated by international collaboration and demonstration at Vandenberg Air Force Base, June 2004.
- IPv6 and IPsec tested in orbit, March 2007.
- Cisco router works well in orbit.
- Has introduced Cisco to the aerospace industry.



Overview

- The Disaster Monitoring Constellation.
- Steps in extending the Internet into space.
- CLEO – Cisco’s mobile access router.
- The existing network environment for the DMC.
- How the Cisco router was fitted to the satellite.
- Virtual Mission Operations Center demonstration.
- Latest testing with CLEO – IPv6, IPsec, DTN.
- Further developments beyond CLEO.

Images shared by other organisations are used with thanks.

Disaster Monitoring Constellation

Disaster Monitoring Constellation (DMC)

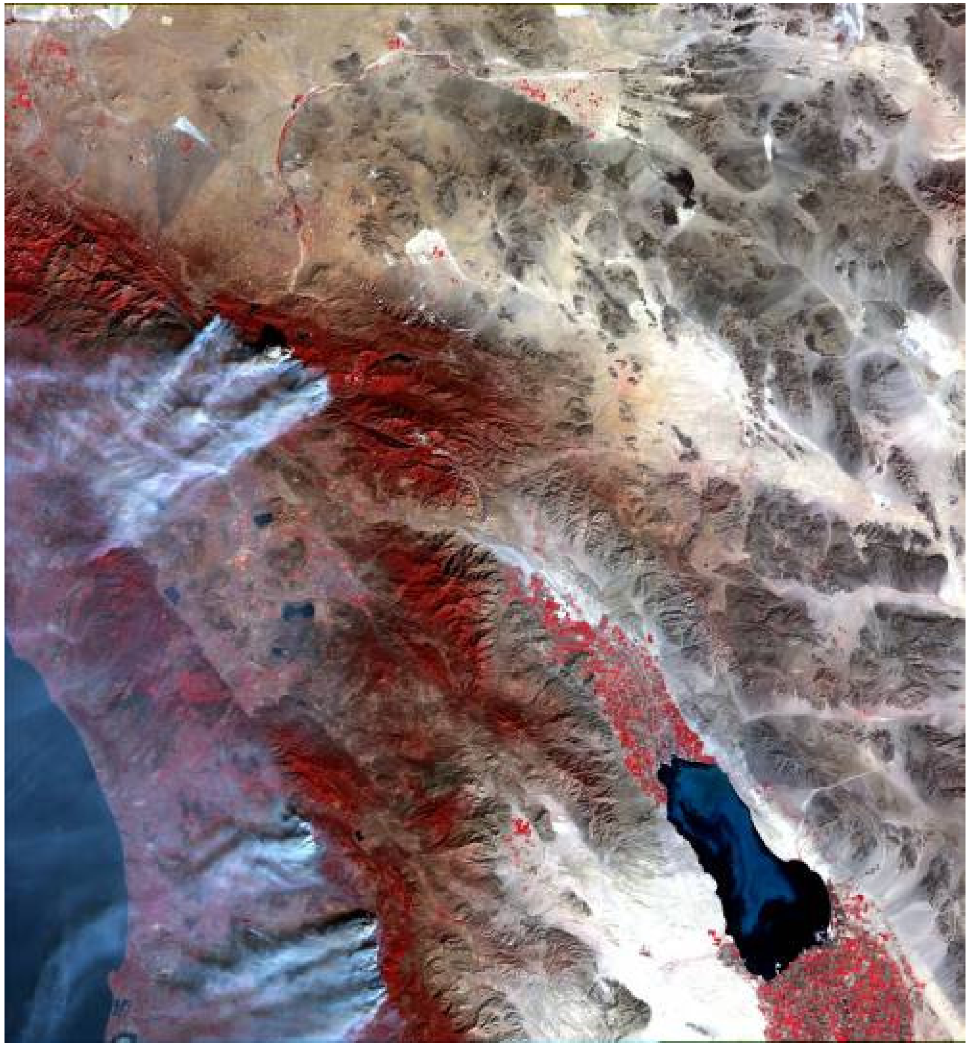
Surrey Satellite Technology Ltd (SSTL) build and help operate an international constellation of small sensor satellites.

The satellites share a sun-synchronous orbital plane for rapid daily large-area imaging (640km swath width with 32m resolution). Can observe effects of natural disasters.

Government co-operation: Algeria, Nigeria, United Kingdom, Turkey and China.

Each government finances a ground station in its country and a satellite. Ground stations are networked together. Further satellites planned.

www.dmcii.com



fires in California, 28 October 2003 (UK-DMC)

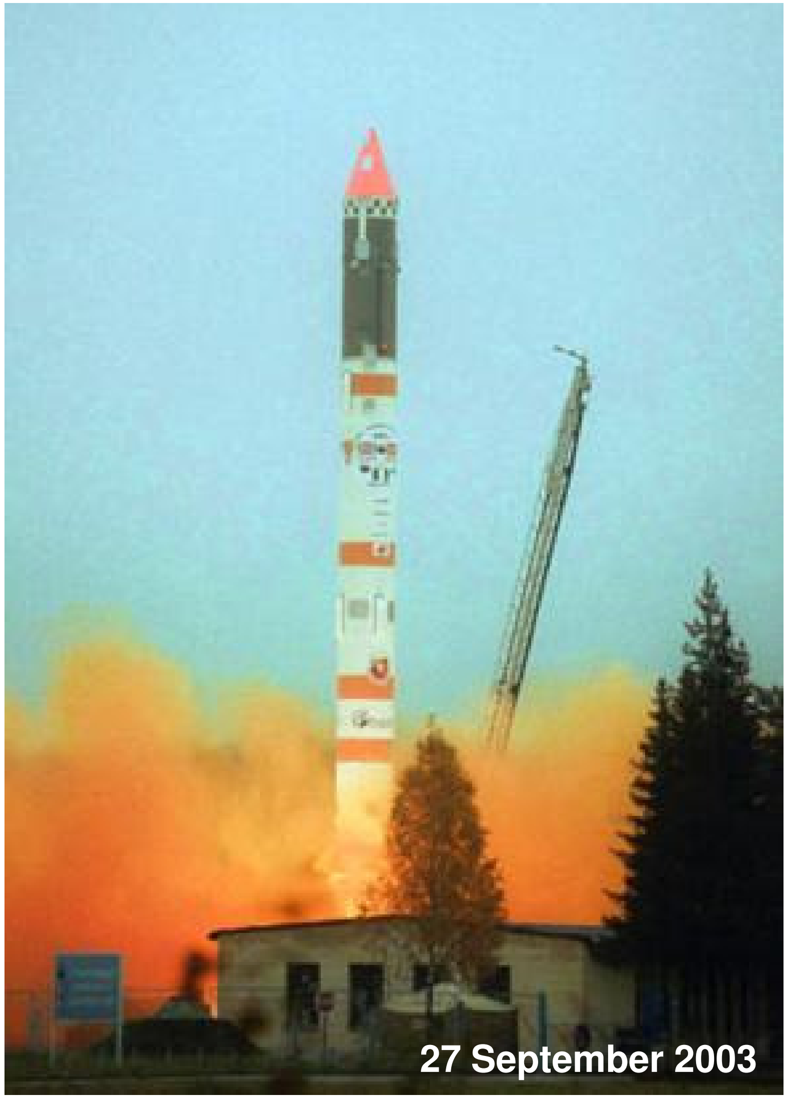
DMC satellite constellation launches

Five satellites launched so far. Similar base designs and subsystems, with custom modifications for each country.

Satellites launched from Plesetsk in Siberia on affordable shared Russian Kosmos-3M launches:
November 2002: AlSAT-1 (Algeria)
September 2003: UK-DMC, NigeriaSAT-1 and BilSat (Turkey)
October 2005: Beijing-1 (China)

Satellites and ground stations in each country use Internet Protocol (IP) to communicate. Earth images delivered to ground stations via UDP-based file transfer.

SSTL migrated from AX.25, as used on previous missions. Use of IP makes a natural fit with Cisco's IP router onboard UK-DMC satellite.



27 September 2003

DMC can image anywhere on Earth

Palm Island Resort, Dubai, 14 Dec 2003 (UK-DMC)

Three Gorges Dam, China, July 2004 (UK-DMC)

www.dmcii.com

DMC in use: after Hurricane Katrina, 2005

In this false-color image, dry land is red. Flooded and damaged land is shown as brown.

Small part of an image taken by the Nigerian DMC satellite on Friday 2 September, for the US Geological Survey.

DMC is working as part of the United Nations International Charter for Space and Major Disasters.

Imagery delivered by using Internet Protocol.

Extending the Internet into space

- NASA JPL gives DERA's STRV-1b an IP address (1996).
- NASA Goddard flies IP stack on SSTL's UoSAT-12* (2000). This encourages SSTL to adopt IP.
- Cabletron router on Russian module of ISS. NASA uses IP in shuttle experiments, e.g. VoIP with Cisco SoftPhone tested from *Atlantis* (Feb 2001). These culminated in CANDOS,* tested onboard *Columbia* (Jan 2003).
- NASA gets SpaceDev to launch CHIPSat (Jan 2003).
- SSTL adopts IP with DMC (AlSAT-1 launched in Nov 2002, UK-DMC *et al.* Sep 2003, Beijing-1 Oct 2005). Cisco and SSTL fit CLEO mobile access router on UK-DMC satellite, alongside imaging payloads.
- MidSTAR-1* and SSTL's CFESat launch (March 2007).

*Keith Hogie's team at NASA Goddard was instrumental in use of IP in these projects.

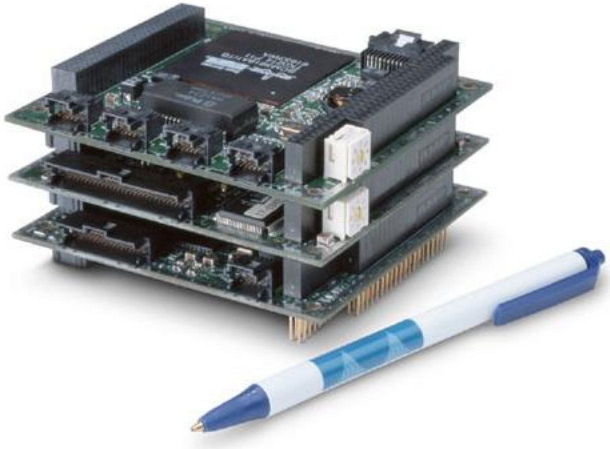
What is the CLEO router?

A Cisco 3251 Mobile Access Router (MAR).
The MAR is a commercial off-the-shelf (COTS) product family – 3251 and 3220 series. Runs Cisco's IOS (Internetwork Operating System) router code – version 12.2(11)YQ.

The 3251 MAR features:
• 210MHz Motorola processor.
• Built-in 100Mbps Ethernet.
• PC/104-Plus interfaces and form factor.
• Additional stackable 90mm x 96mm cards (serial, Ethernet, power supply, WiFi, etc.)

The CLEO MAR is an experimental secondary payload on the UK-DMC satellite.

Local environment and high-speed downlink used by UK-DMC satellite dictate use of serial interface card to connect with existing 8.1Mbps serial links used onboard.



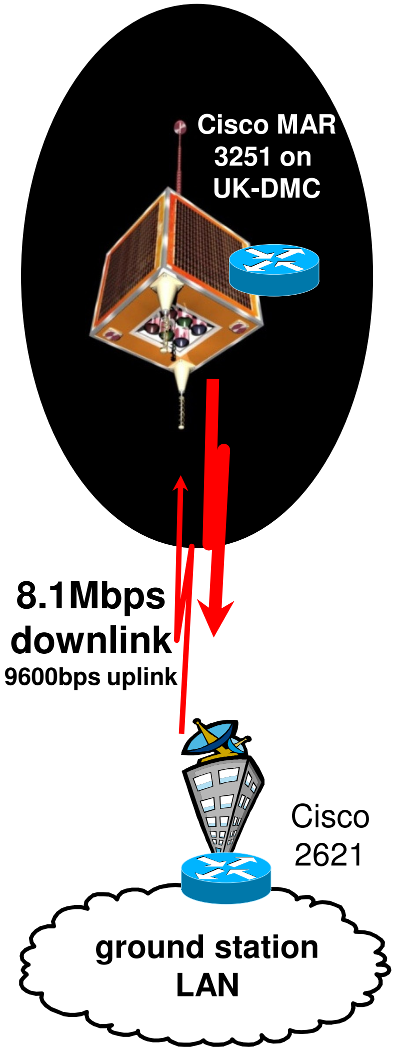
Other tests of Mobile Access Routers

NASA Glenn Research Center tested MAR on Neah Bay icebreaker in Great Lakes. Mobile routing roamed seamlessly between wired link when docked, and long-range WiFi and Globalstar satellite links when sailing.

Cheever Racing put WiFi and VoIP, for secure telemetry, voice, and video, in its cars, pit and garage. Two cars carrying MARs were raced in the 89th Indianapolis 500.

How the Cisco router was fitted to the satellite

Existing network environment for the DMC



Satellite: each DMC satellite has multiple onboard computers. For housekeeping (the On Board Computer, OBC), for image capture and packetised transmission (the Solid State Data Recorders, SSDRs), for redundancy and survival. Interconnected by IP over 8.1Mbps serial links for data and slower CANbus for backup control; really a custom-built LAN.

CLEO: Cisco router was able to fit into UK-DMC satellite's onboard network by connecting to OBC and SSDRs using common serial interfaces.

Ground: SSTL's design for its ground station LANs uses IP. Satellites communicate with PCs on LAN via S-band radio space-ground link. IP over 8.1 Mbps serial stream from downlink commercial modem goes into a rack-mounted Cisco 2621 router, which forwards IP packets onto the LAN. SSTL's ground station LAN is connected to and an integral part of SSTL's corporate IP network.

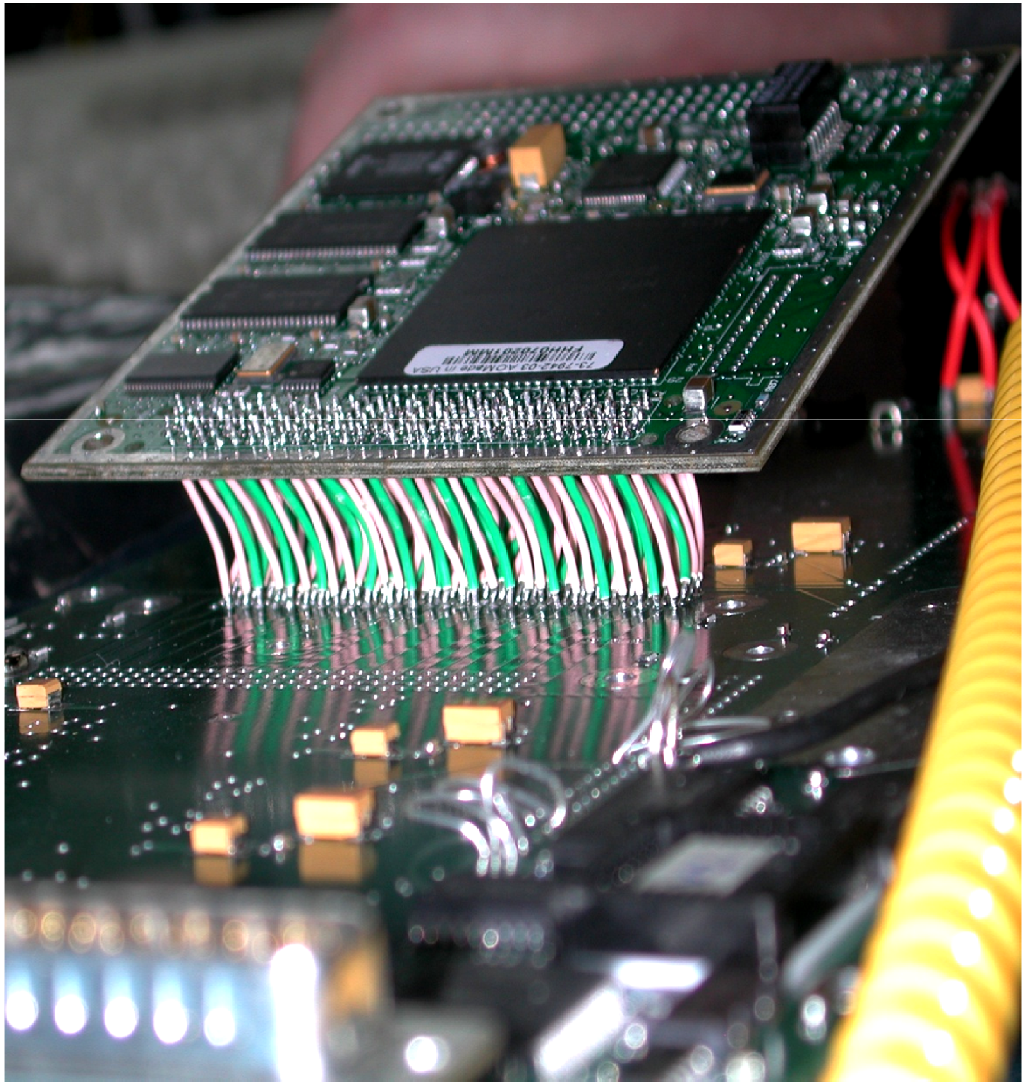
Alterations to CLEO for launch and space

No radiation hardening; low orbit environment is relatively benign.

No unique hardware design or software work done by Cisco.

Minor physical modifications made to router and serial card.

- Flow-soldered with lead-based solder to avoid 'tin whiskers'.
- Flat heatsink added to main processor to take heat to chassis.
- To avoid leakage in vacuum, wet electrolytic capacitors with pressure vents replaced with dry.
- Unused components removed, including plastic sockets and clock battery. Time set with NTP. Directly soldered wires are more robust for vibration/thermal cycling.

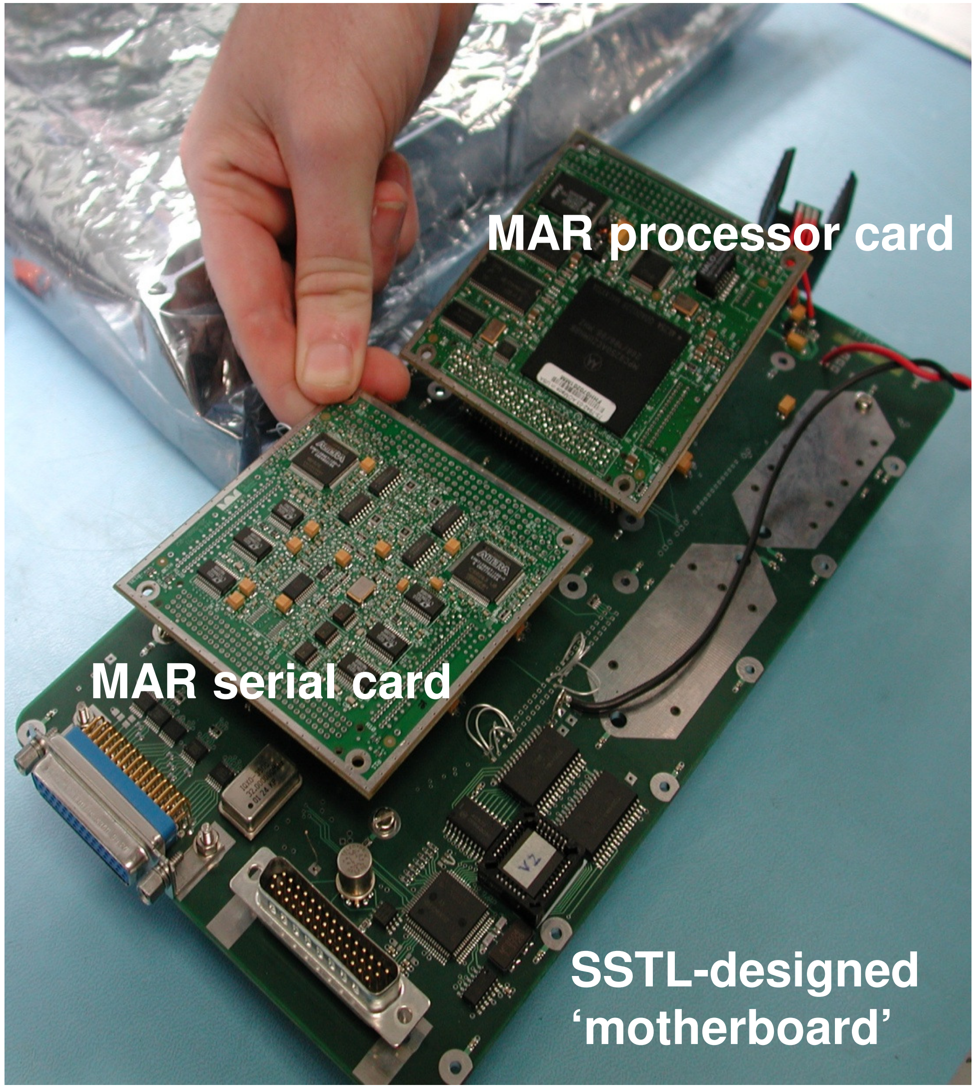


CLEO integration 1 – the router assembly

MAR processor card and serial card wired to ‘motherboard’ designed by SSTL.

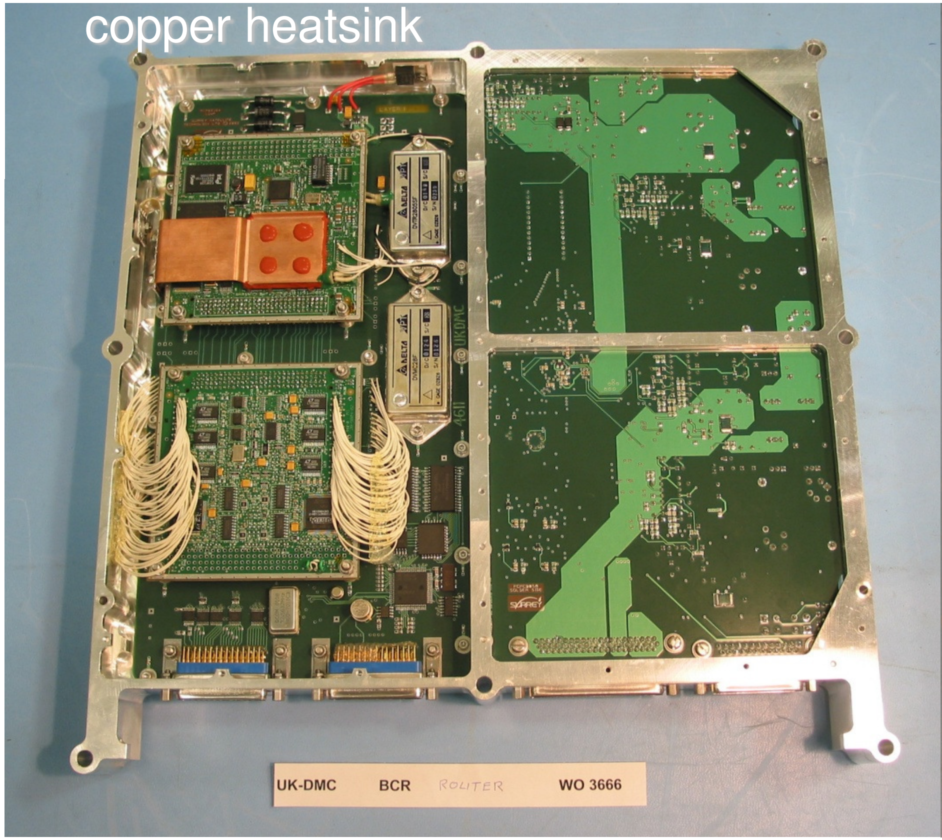
‘Motherboard’ provides physical mounting, power, serial connections and serial/CANbus interface for access to router console port.

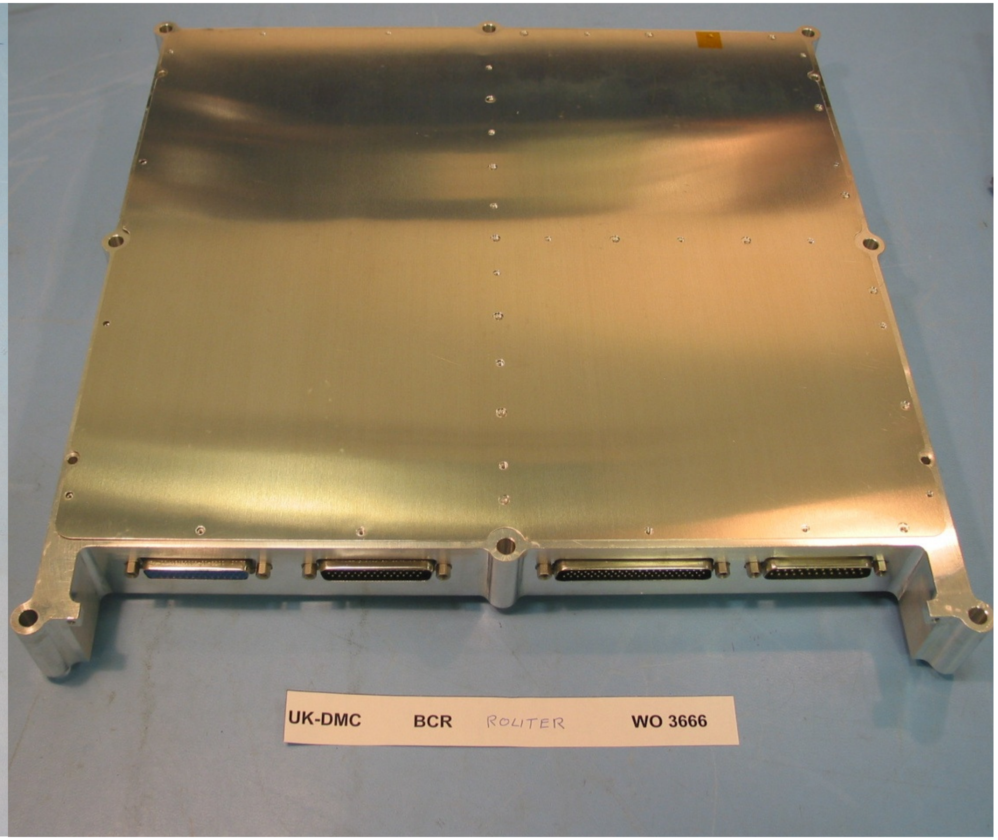
Router console port was used to ‘bootstrap’ router configuration in orbit from nothing. After basic networking was configured during passes, telnet and ssh were then used.



CLEO integration 2 – the payload tray

SSTL's satellites are modular stacks of identical aluminium trays, screwed together. Aluminium provides grounding, heat conduction, and structural rigidity. Satellites are built rapidly, using COTS parts, in under 18 months. Router card assembly takes up half of stackable tray.



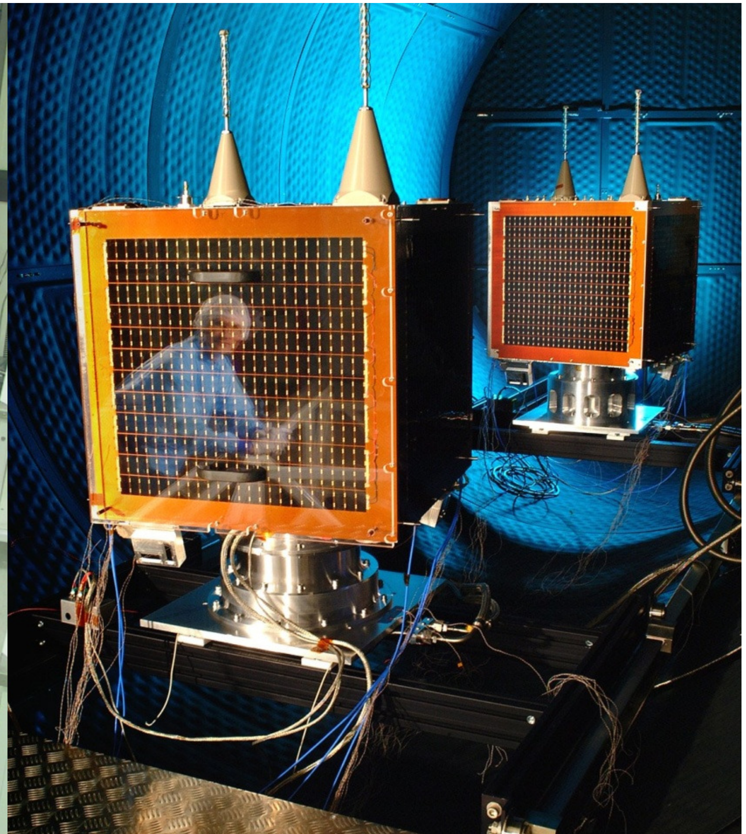


CLEO integration 3 – testing before launch

Satellite assembly, subsystems and router operated in partial vacuum of less than $1x10^{-5}$ torr ($1x10^{-3}$ Pa), temperature range of $-35^{o}C$ up to $+60^{o}C$.
Also vibration tested.

satellite assembly

in-house testing



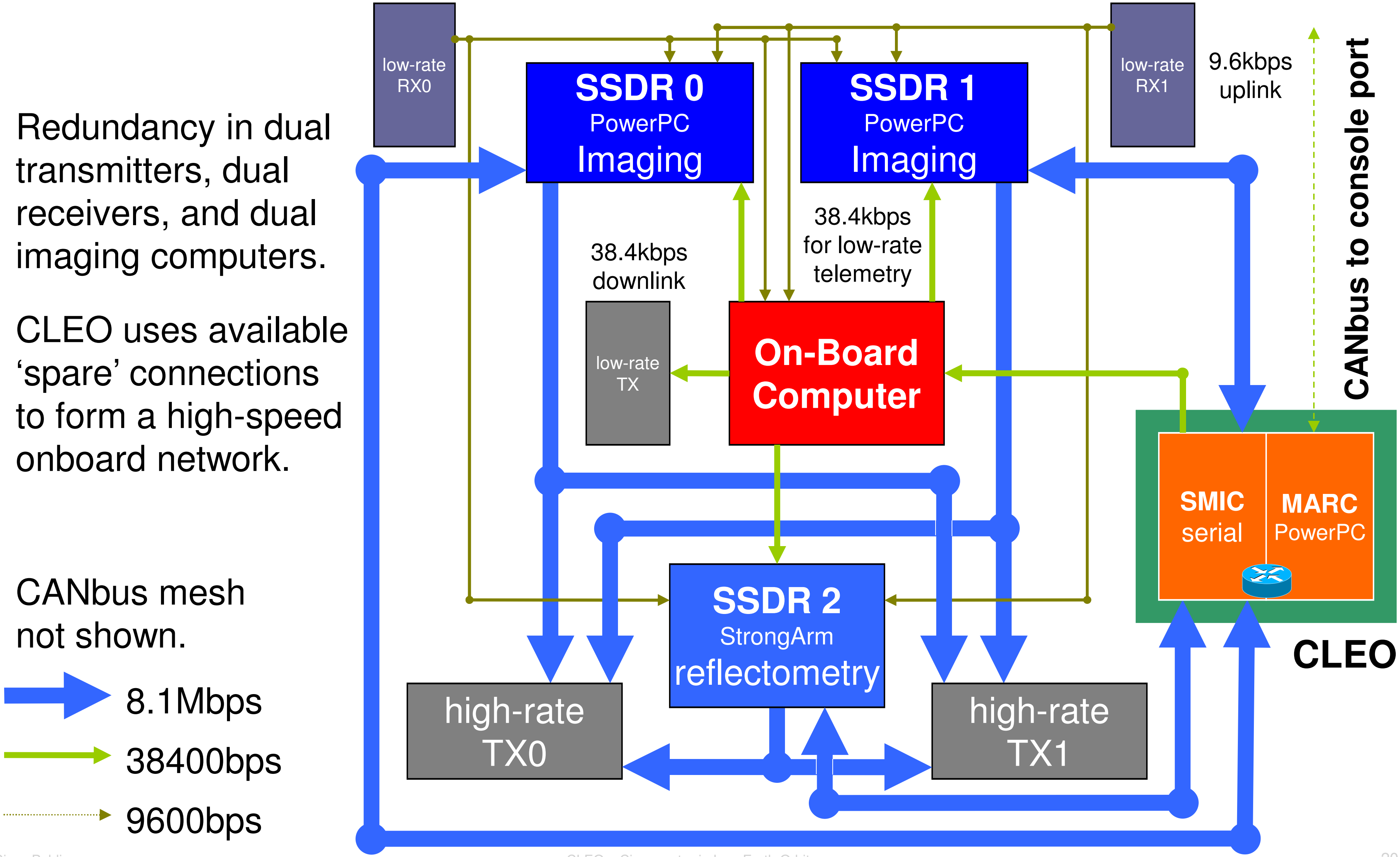
vacuum chamber testing

UK-DMC payloads… connected to CLEO

Redundancy in dual transmitters, dual receivers, and dual imaging computers.

CLEO uses available ‘spare’ connections to form a high-speed onboard network.

CANbus mesh not shown.



Limits to use of CLEO

As a secondary experimental payload, CLEO spends most of its time turned off. CLEO is only active when being tested during passes over ground stations, or when being used to transfer data between SSDRs.

The mobile router is a commercial product, not a space instrument. CLEO does not contain any special instrumentation for the space environment. CLEO does not measure cumulative radiation dosage.

SSTL does have some additional thermal and power draw instrumentation around the CLEO assembly motherboard.

Available satellite power is a constraint – CLEO is powered up for around ten minutes at a time during a daytime sunlit pass to communicate with ground station using high-speed 8.1Mbps downlink. CLEO needs ~10W. High-speed downlink needs ~10W. UK-DMC power budget is only ~30W.

Onboard software cannot be easily upgraded – no plans to *ever* upload 6MB router IOS software over multiple passes via 9600bps uplink.

Ground-based testbed for configurations

NASA Glenn needed to gain familiarity with operating and configuring router with SSTL's onboard computers.

Ground-based testbed allows configuration changes to be tested on the ground at leisure before being made to CLEO during a ten-minute pass over a ground station.

Built rack-mounted ground-based testbed ('flatsat') from SSDR and engineering model of mobile router, and networked it from NASA Glenn in Ohio.

Built testbed after launch!
Configured CLEO after launch!
Testbed later useful for DTN work.

VMOC and Vandenberg demonstration

Virtual Mission Operations Center (VMOC)

Software developed by General Dynamics intended to task satellites and provide imagery via a simple GUI interface for military users.

VMOC was rated second out of 120 projects in importance by the US Office of the Secretary of Defense, Rapid Acquisition Incentive - Network Centric (RAI-NC) program. So became one of four pilots receiving advance funding.

VMOC intended for use with TacSat-1 (not yet launched), and then TacSat-2 (launched Dec 2006). UK-DMC provided early opportunity to test VMOC.

VMOC requests images of ground from SSTL mission planning system for DMC satellites. Images are taken for VMOC by UK-DMC only. VMOC monitors UK-DMC satellite telemetry and accesses CLEO router.

VMOC is simply an IP-based application for satellites, using an available IP-based satellite infrastructure!

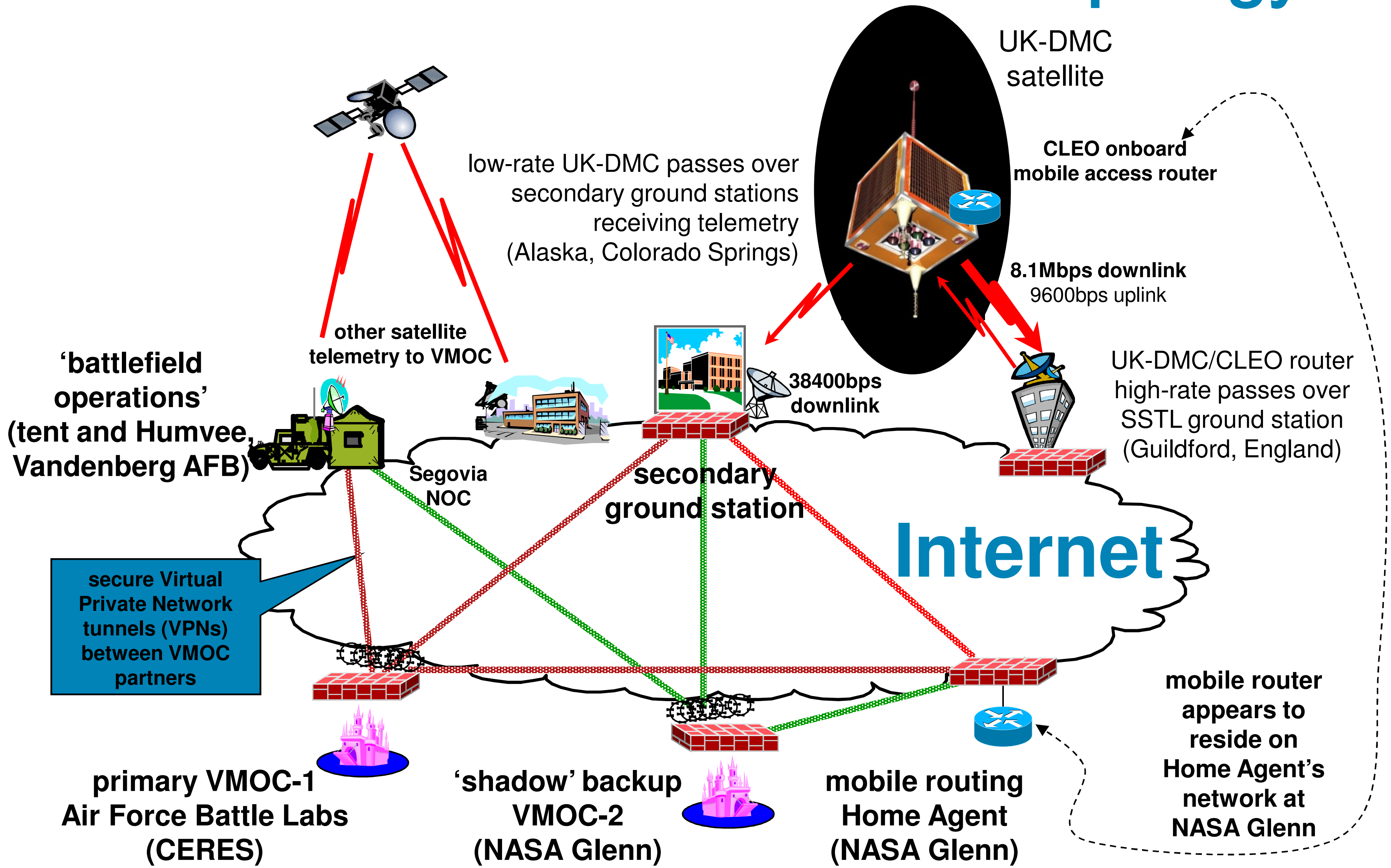
VMOC demo, Vandenberg Air Force Base

May-June 2004, VMOC, image request and access to onboard payload (router) were tested by coalition of partners ‘in the field’ in tent and Humvee at Vandenberg Air Force Base in California.

Tested:
- requesting sensor data (imagery) from the UK-DMC satellite.
- use of IP for field operations.
- tasking a satellite payload (the CLEO router, accessed using mobile networking).
- failover between multiple VMOCs.

Testing and demonstration were successful. Cisco’s CLEO router in orbit shown to work by third parties while testing a larger integrated ‘system of systems’.

VMOC demonstration network topology



CLEO and VMOC – meeting needs of participants

Commercial
Cisco Systems
Show that a commercial COTS Internet router can work in space.

Civil
NASA Glenn
Demonstrate utility of IP and mobile routing for satellite TT&C.

Military
Air Force Space Battlelab
Test the Virtual Mission Operations Center in the field and task space asset.

SURREY SATELLITE TECHNOLOGY LTD

CLEO: Cisco router in Low Earth Orbit placed on UK-DMC satellite by SSTL

Cisco gets its router launched as secondary experimental payload.

NASA Glenn uses router in space to test mobile routing for satellites.

VMOC is tested across Internet from Vandenberg with CLEO & UK-DMC.

CLEO router works in space. VMOC works with space asset. Mission success!

Demonstration involved many organisations

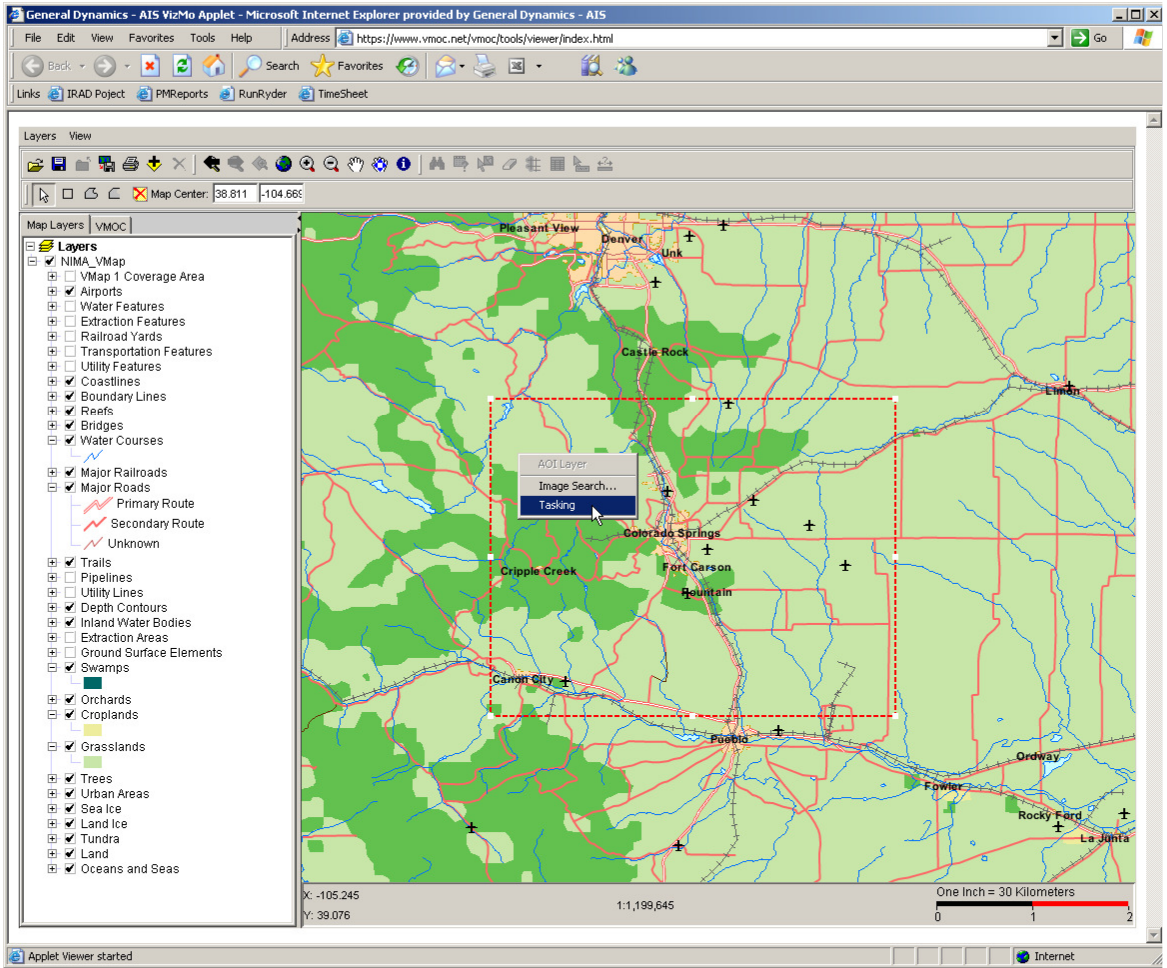
Other demonstrations to US military

5 November 2004, VMOC imaging request operations were demonstrated at Air Force Space Command Headquarters in Colorado Springs to Gen. Lance Lord.

18 November 2004, to Air Force Space Command during its Commanders' Conference in Los Angeles.

2 December 2004, to the leadership of the Air Staff and Joint Staff in the Washington, DC area.

17-20 October 2005, exhibited at IEEE MILCOM.



Tasking to request an image of Colorado

Acknowledgment of success of CLEO and VMOC

Computerworld Heroes recognition **GD Technology award** **NASA TGIR award**

- Winner of NASA's *Turning Goals into Reality* 2005 awards.
- NASA Glenn and SSTL were finalists in Computerworld Heroes awards, 2005 and 2006.
- Internal awards within Air Force and General Dynamics.
- Internal awards for project management.

Status of CLEO

CLEO remains operational.

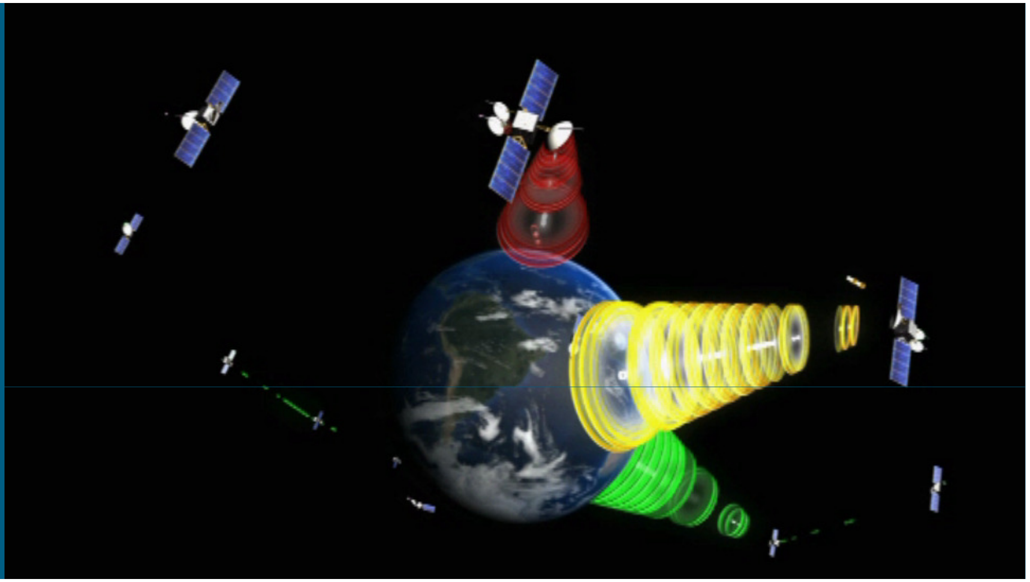
CLEO was first to show IPv6 and IPsec from space.

As a secondary experimental payload, use of CLEO is on a best-effort basis, balanced against the other demands on the UK-DMC satellite. When not being tested, CLEO is simply switched off to save power.

CLEO has now been in orbit for over five years. CLEO and UK-DMC have both exceeded the planned satellite design lifetime. Operation of CLEO has continued over four years.

CLEO has been powered up for use on more than one hundred occasions.

Further developments



Other CLEO testing – GPS reflectometry

UK-DMC satellite also has onboard a GPS reflectometry experiment, measuring backscatter of GPS signals from ocean waves to determine wind speed and wave height.

Moving data from the slow ARM-based SSDR running that experiment to ground required dedicating passes over ground stations to that SSDR.

Data can be moved through the router to be stored on a faster primary imaging SSDR while the satellite is not passing a ground station – uses router without using high-speed downlink, takes advantage of router being connected to all onboard computers in onboard LAN.

Increases download speed – what was a dedicated ground station pass is now a fraction of a normal imaging pass.

Autonomous networking and data transfer first operated in October 2005. Used regularly, showing that CLEO is still operational.

IPv6 and IPsec testing with CLEO

IPv6 and IPsec have now been tested onboard CLEO.
First to test IPv6 on a satellite, 29 March 2007.

IPv6 – CLEO, ground Cisco routers and PIX firewalls are IPv6-capable, although SSTL and UK-DMC payloads rely only on IPv4.

IPsec – CLEO and ground station routers can use this to secure unencrypted ground-space link by tunnelling IP traffic through the router. (*ssh* to CLEO and a passworded web interface were configured in 2004.)

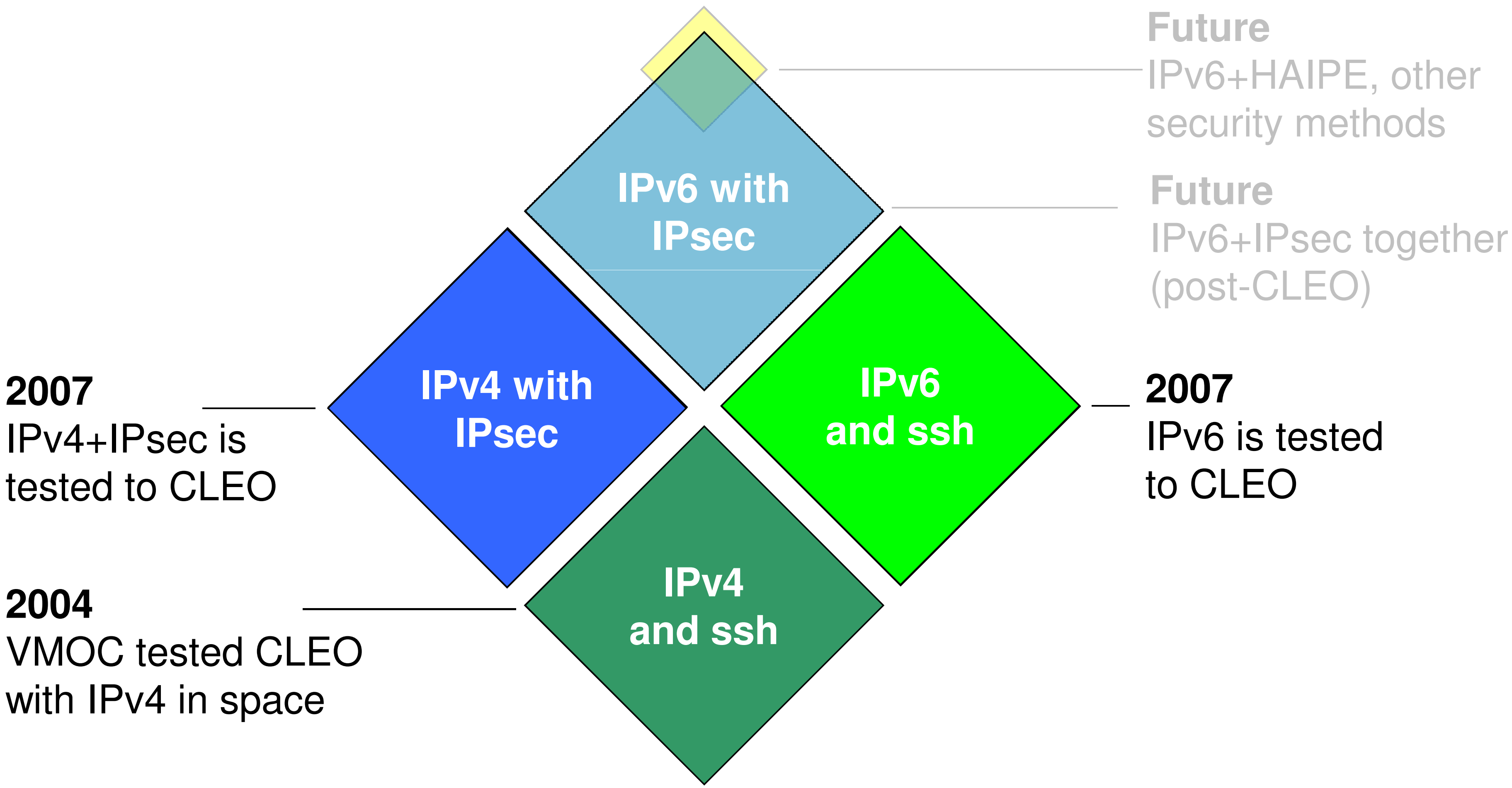
Separate frame-relay/HDLC subinterfaces are used to the satellite:
- unencrypted IPv4 and IPv6.
- IPv4 encrypted with IPv4 IPsec, able to carry IPv6 in a 6-to-4 tunnel.

(IPv6 IPsec was introduced in more recent code releases, and not flown.)

Could also use SNMP and MIBs to show that a satellite payload can be managed just as you would manage a terrestrial network asset.

CLEO shows roadmap for IPv6 and IPsec

IPv6 and IPsec are now working in orbit



CLEO, the Cisco router in Low Earth Orbit, is able to show three of these steps.

Why move satellites and infrastructure to IPv6?

- Because the US DoD mandates IPv6 for its use:

  addressing improved, routing tables smaller/simpler.

  NAT not (yet!) needed to integrate legacy networks.

  IPsec should be an integral part of IPv6, not an afterthought.

  link-local addressing eases ad-hoc connectivity and dynamic routing for MANET.

  Mobile IP becomes less messy.

  Diffserv and per-flow stuff easier to do.

  Lots of little advantages, which all add together.

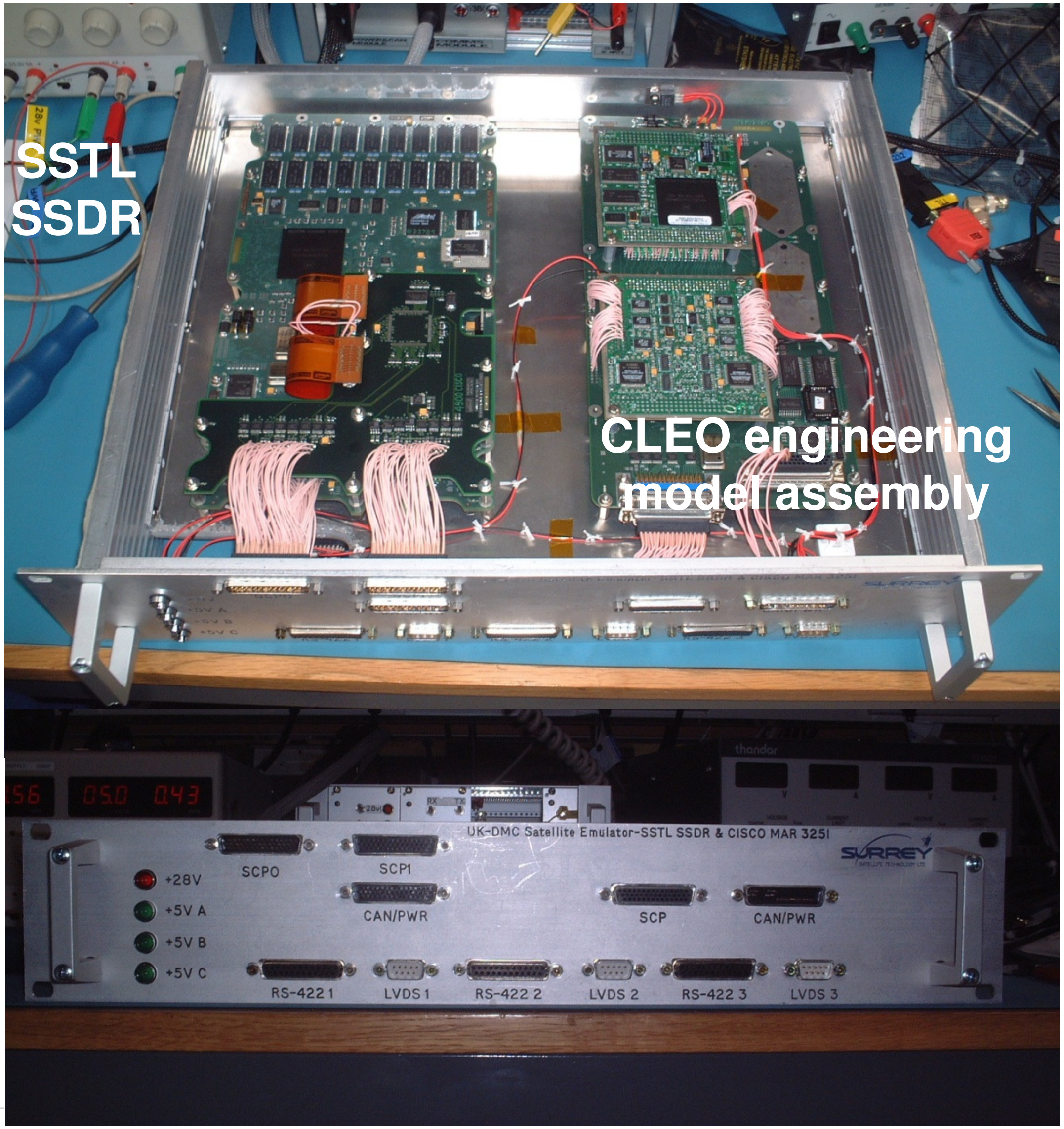
- For rest of world outside US:

  Owning enough address space and manageable routing tables in the backbone are key here.

  US has large IPv4 installed base; playing catch-up.

Ground testbed enables new development

- Ground-based testbed loaned to NASA Glenn was key to success of VMOC testing to deadline.
- IPv6 configs prepared and tested by NASA Glenn, before being copied to CLEO on orbit.
- Testbed now being used for software development.
- Delay-Tolerant Networking Research Group's 'Bundle Protocol' being tested.



Delay-tolerant networking (DTN)

- DTN began intended for deep-space connectivity, now also used for opportunistic ad-hoc networks.
- Data is moved like store-and-forward email messages in ‘bundles’ between nodes when limited connectivity becomes available and links are up.
- DTN research group investigating this in IRTF.
- NASA Glenn has ported DTN bundling code to SSTL’s onboard computers, using CLEO testbed.
- Many ‘convergence’ (transport) layers for DTN – SSTL’s custom *Saratoga* UDP transfer is a simple, high-performing choice.
- **First tests of the Bundle Protocol in space, prototyping the ‘Interplanetary Internet.’**

www.dmcii.com

150MB image transferred from UK-DMC satellite using Bundle Protocol over *Saratoga* with proactive fragmentation, 25 August 2008. **First sensor data in bundles from space.**

TIME Magazine best inventions of the year **#9 Orbital Internet**, 10 November 2008 issue.

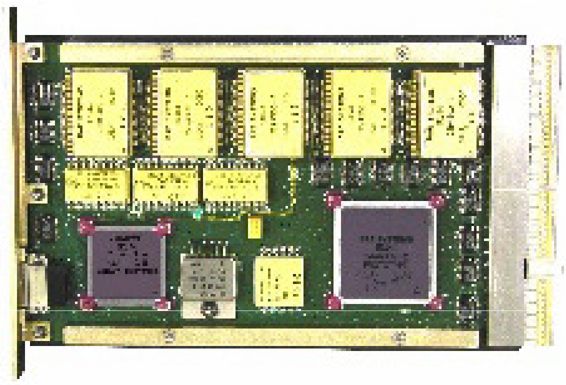
Beyond the success of CLEO

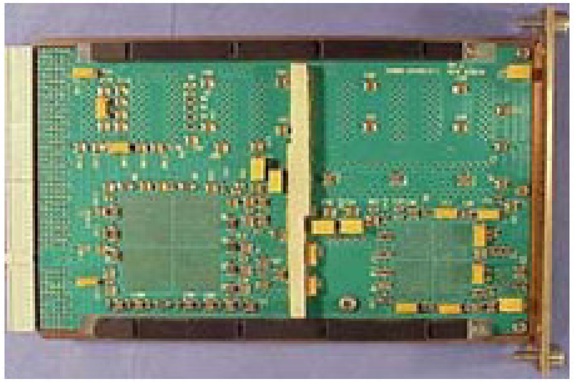
The outcome of the CLEO project and testing has encouraged Cisco Systems to prototype and evaluate IOS software running on radiation-hardened PowerPC processors and hardware *very* different from this first demonstration.

Cisco Systems is interested in working with others to take IP and routing functionality to new places… including high altitude and with **IRIS**, (IP Routing in Space) to geostationary orbit.

Port of IOS to a rad-hard processor

- **Aqueduct** project in cooperation with NASA Goddard, intended as proof of concept for future embedded space systems.
- Demonstrates IOS in an embedded application, using software derived from 12.3(11.4)T.
- Main processor is 133MHz PowerPC-based RAD750 from BAE Systems.

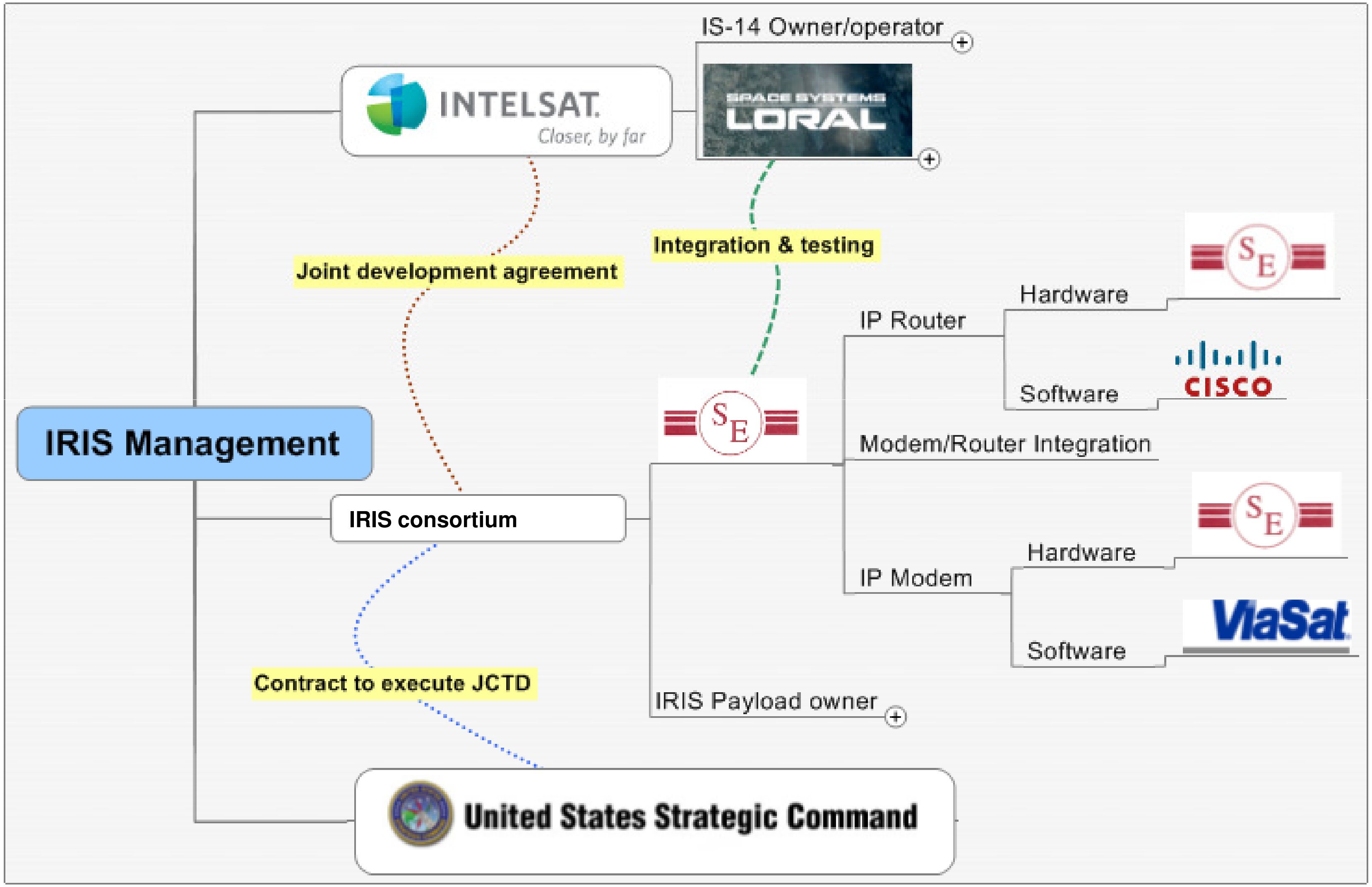




IRIS – IP Routing In Space

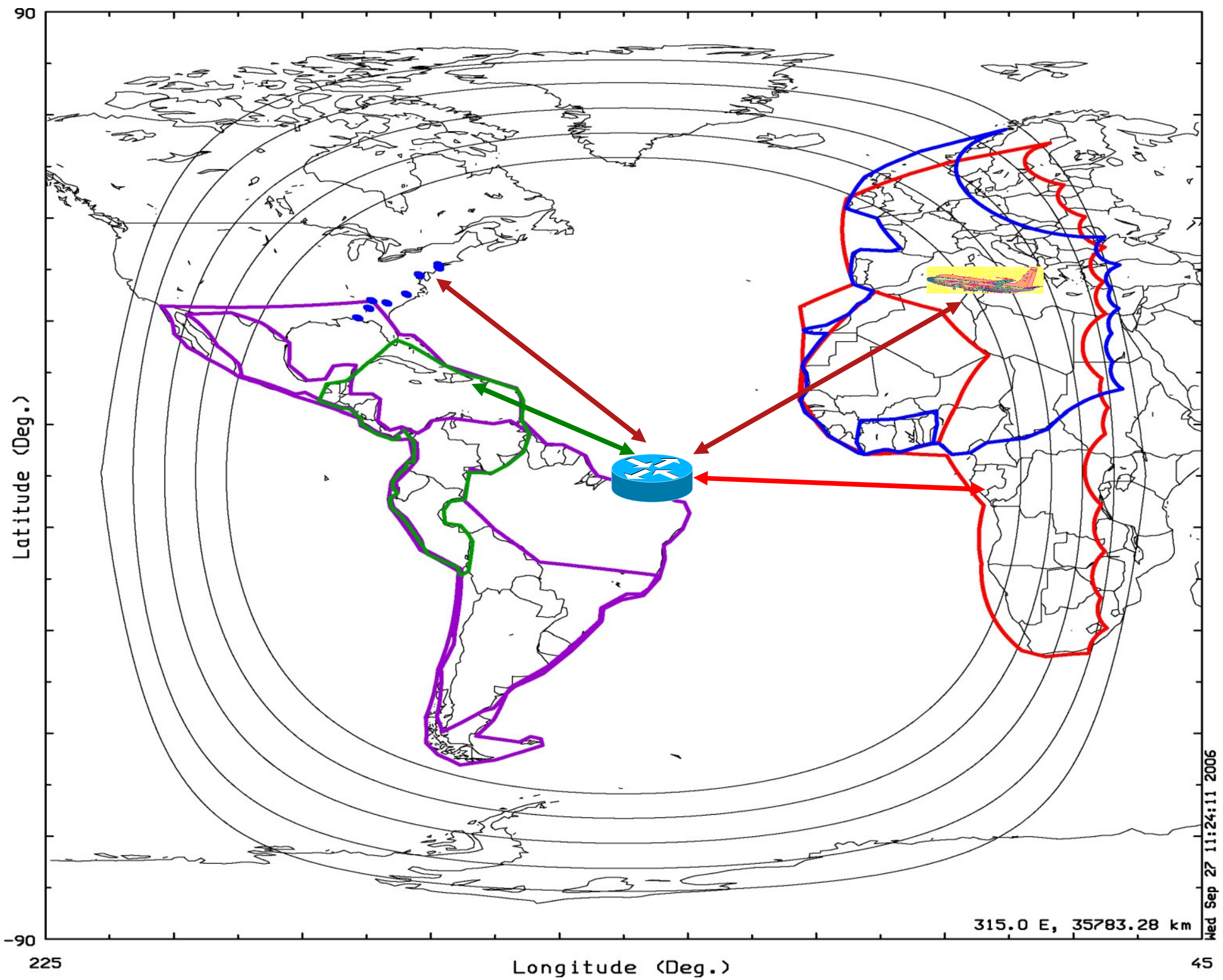
- A US Strategic Command study investigated putting hosted payloads on commercial communications satellites for military use.
- This idea was pursued, with the aim of having the military as a customer.
- Targeted Intelsat-14 (launched 2009), with a router in geostationary orbit. A commercial development effort.
- Based around a PowerPC G4 processor. Increased use of FPGAs and ASICs for later payloads, which are also expected to add laser intersatellite links.

Partners in IRIS



IRIS hardware development by SEAKR Engineering in Colorado.

IRIS expected coverage on Intelsat-14



further information:

just google “cleo router”

Questions?

thankyou