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Testing the Cisco router in orbit thoughts on extending the Internet into space

Lloyd Wood

<http://www.ee.surrey.ac.uk/Personal/L.Wood/>

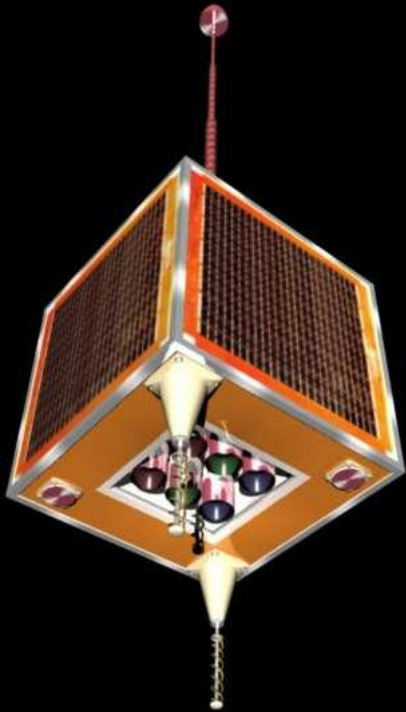
Space team, Global Defense, Space and Security, Cisco Systems

<http://www.cisco.com/go/space>

Surrey Space Centre guest lecture
Tuesday, 15 November 2005

Brief summary

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- **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 internetworking of satellite and router tested and validated by international collaboration and demonstration at Vandenberg Air Force Base, June 2004.**
- **IP works for satellite and payload communication and control.**
- **Cisco router works in orbit.**

Overview

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- **The Disaster Monitoring Constellation**
- **The Cisco router in Low Earth Orbit (CLEO)**
- **Steps in extending the Internet into space**
- **The existing network environment for the DMC**
- **Router modifications and satellite integration**
- **Virtual Mission Operations Center (VMOC)**
- **Vandenberg demonstration**
- **Awards won by this space payload work**
- **Current status and future thoughts**

Images shared by other organisations are used with thanks.

Disaster Monitoring Constellation (DMC)

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Surrey Satellite Technology Ltd (SSTL) built 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, Turkey, United Kingdom, and China.

Each government pays for a ground station in its country and a 100-140kg satellite. Ground stations are networked together.



www.dmcii.com

DMC satellite constellation launches

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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 – AISAT-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 transfer.

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



27 September 2003

DMC put to use: after Hurricane Katrina, 2005

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New Orleans

- A - 17th Street Canal Breach
- B - London Avenue (E) Canal Breach
- C - London Avenue (W) Canal Breach
- D - Industrial Canal Breach



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.

www.dmcii.com

What is the CLEO mobile access 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.

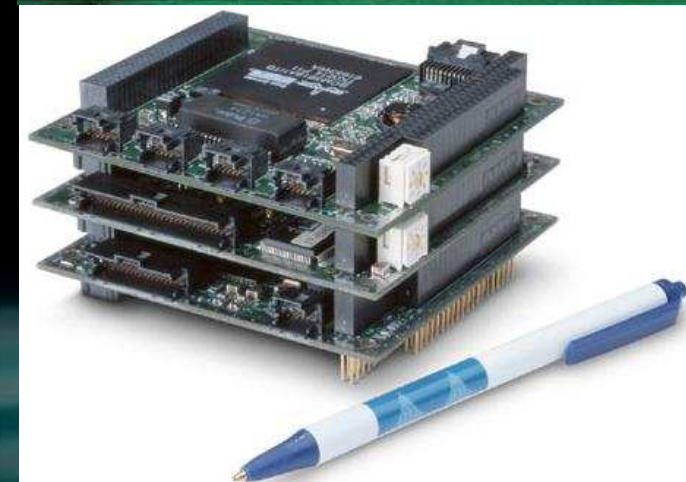
The CLEO MAR is an experimental secondary payload on the UK-DMC satellite.

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.)

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.

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Other tests of Mobile Access Routers

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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.

Steps in extending the Internet into space

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- **NASA JPL gives DERA's STRV-1b IP address (1996).**
- **NASA Goddard flies IP on SSTL's UoSAT-12 (2000).**
- **Cabletron router on Russian module of ISS. NASA uses IP in shuttle experiments, last being CANDOS (tested onboard Columbia, Jan 2003).**
- **NASA gets SpaceDev to launch CHIPSat (Jan 2003).**
- **SSTL adopts IP with DMC (AISAT-1 launched 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.**

NASA Goddard's UoSAT-12 demonstration

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Show *simple* point-to-point wireless IP comms for deep space. ISO-standard HDLC has no setup overhead (while Cisco's own *IOS* HDLC has keepalives and SLARP, and PPP negotiation is far more complex – not suited for sending one-way long-distance comms from Mars).

Use of Frame Relay (FR) with ISO HDLC is standardised and widespread – simple assembly, integration, testing (AIT). Can plug compatible pieces (routers speaking HDLC, modems understanding HDLC) together. Can use FR to indicate you're carrying other than IP, set up virtual channels, even do MPLS-type bridging things.

Cisco 1601 router in ground station, IP stack on UoSAT-12.

Taken further by CANDOS. See Keith Hogie's OMNI (Operating Missions as Nodes on the Internet) papers.

Simple vs complex IP framing strategies

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Point-to-point links, emphasis on simplicity

Simple integration - shown on UoSAT-12

commercial router



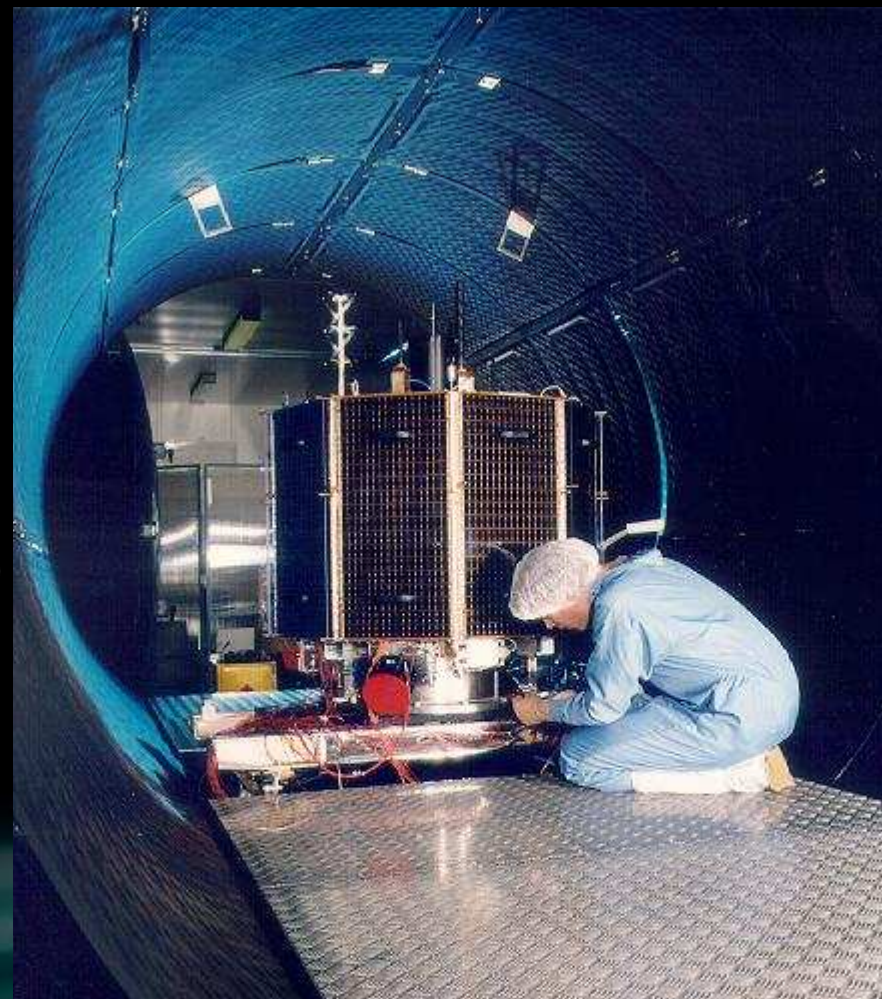
Preamble
(flags, control data)

Trailer
(CRC, flags)

Stream into modem to encode

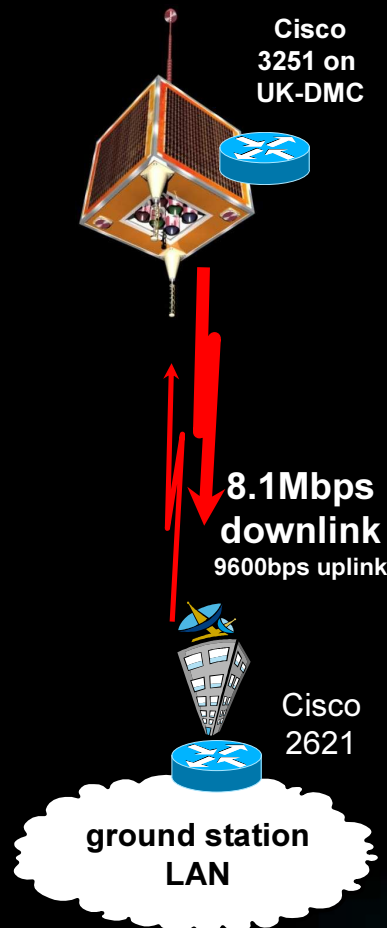
commercial modem

New coding? Buy new modem off shelf.
Just replace the old modem.



Existing network environment for the DMC

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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 part of SSTL's corporate IP network.




UK-DMC payloads... connected to CLEO

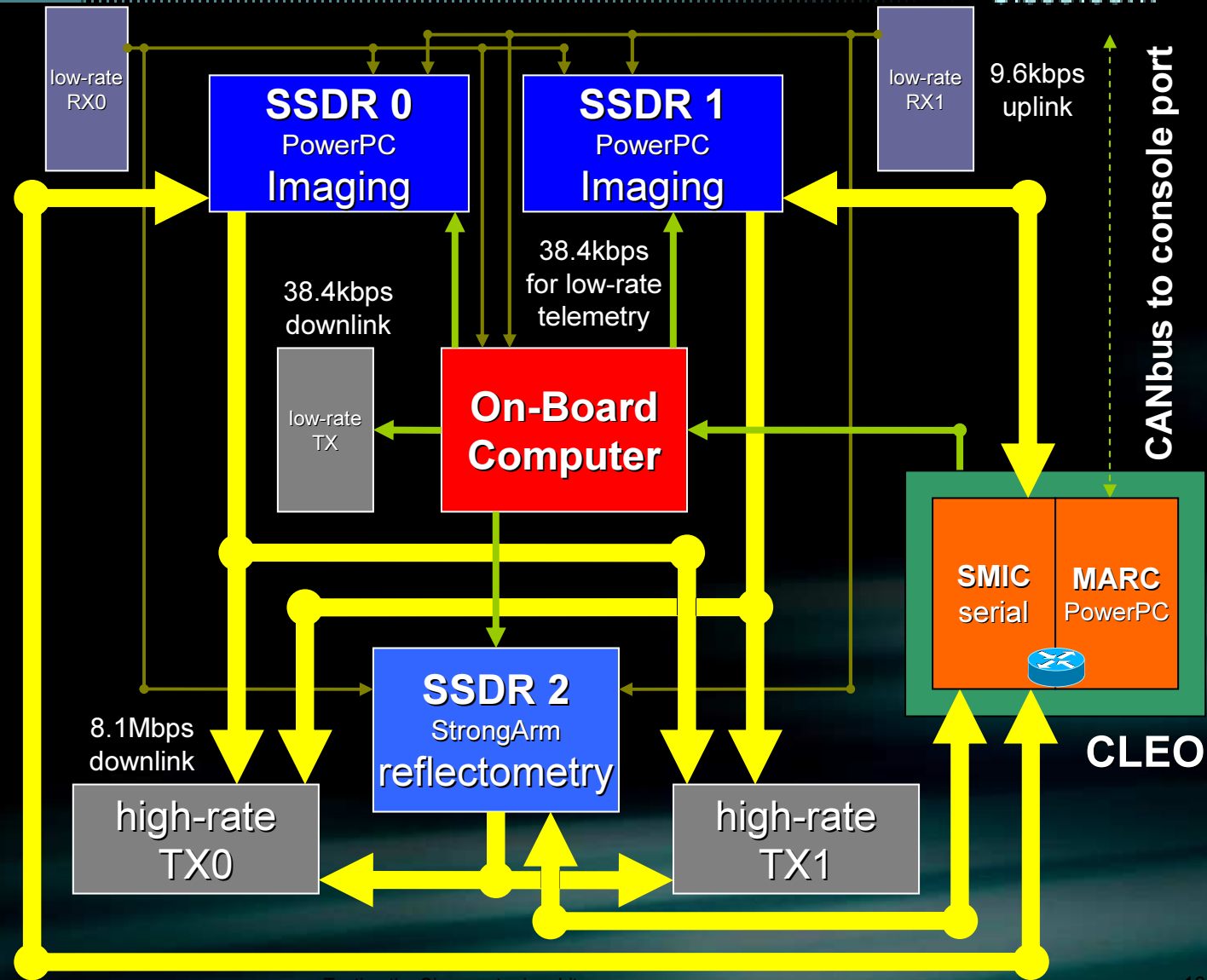
Redundancy in transmitters, in receivers, and in imaging computers

CLEO uses available 'spare' connections to form a high-speed onboard network

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CANbus mesh not shown

-  8.1Mbps
-  38400bps
-  9600bps



Alterations to CLEO for launch and space

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No radiation hardening; low orbit environment is relatively benign.

No unique hardware design or software work done by Cisco.

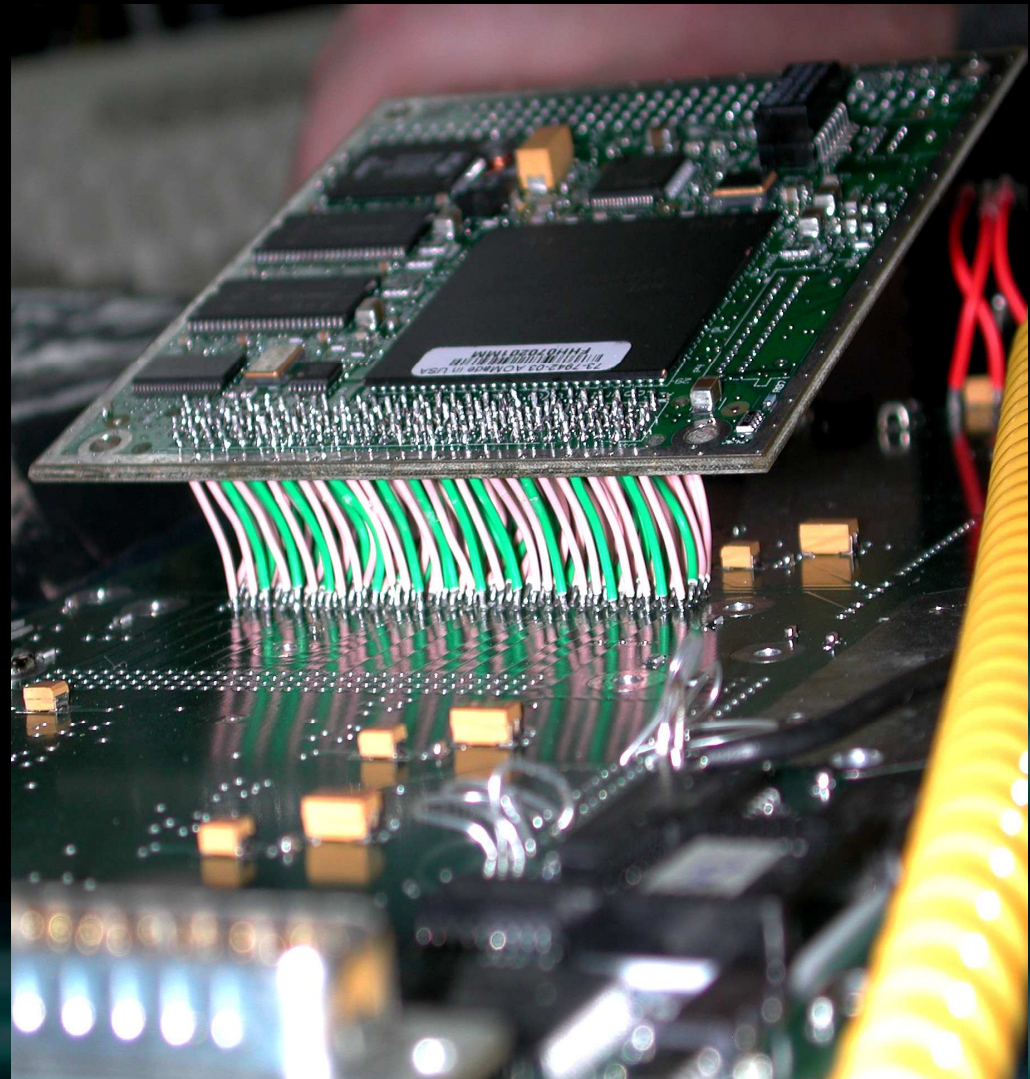
Minor physical modifications made to router and serial card.

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.



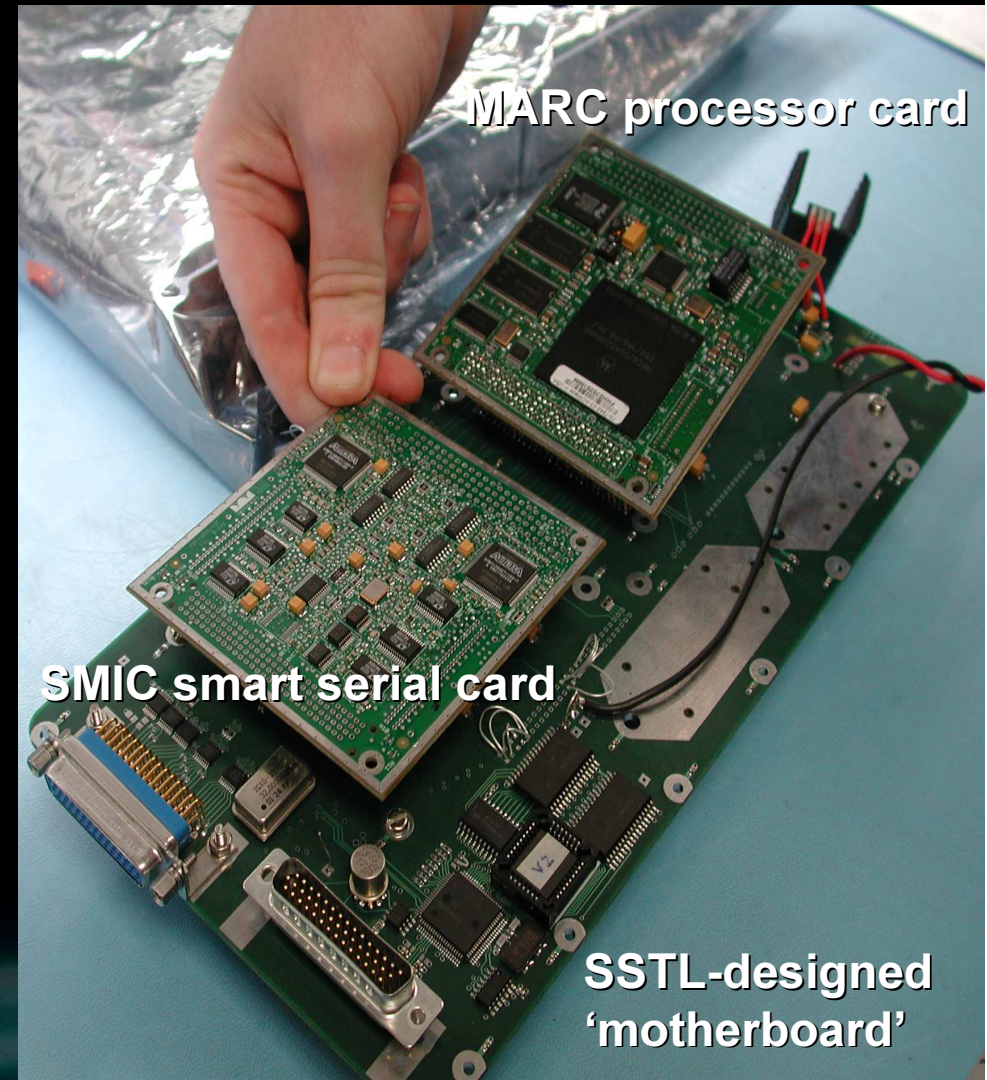
CLEO integration 1 – the router assembly

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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.

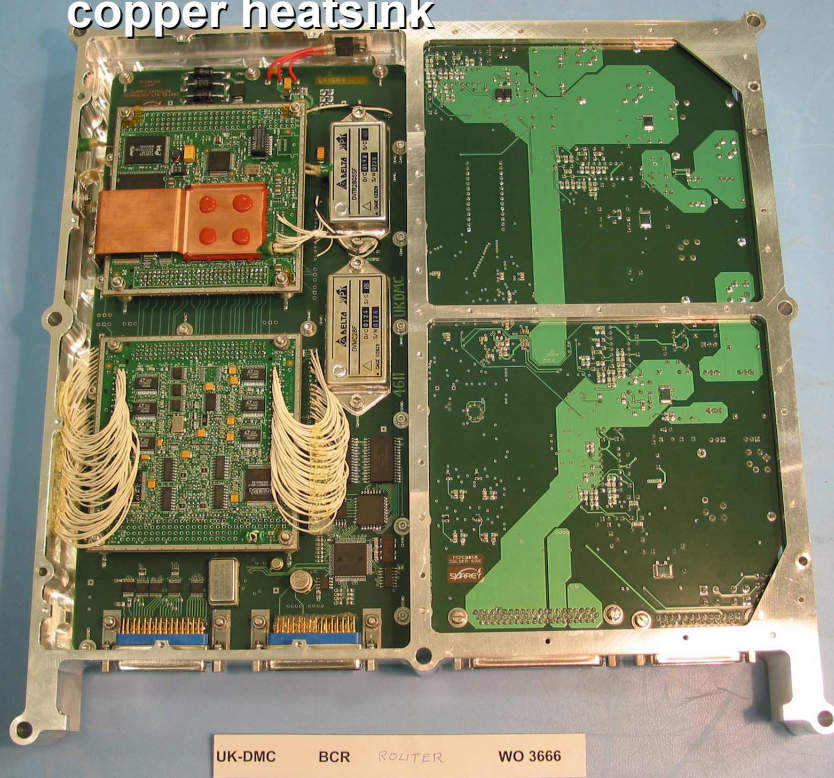


CLEO integration 2 – payload tray to satellite

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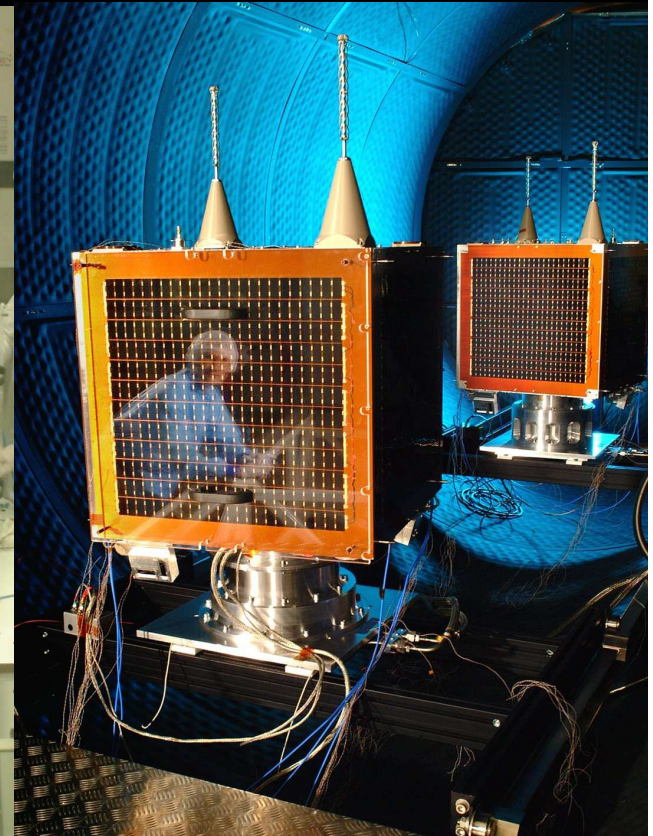
SSTL's satellites are *modular* stacks of identical aluminium trays, screwed together. Aluminium provides grounding, heat conduction, and structural rigidity. Satellites are built *rapidly*, using COTS parts, in under 18 months.

copper heatsink



cameras

propellant tank



CLEO router in half of payload tray

satellite assembly

vacuum chamber testing

Work before and after launch

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Before launch completed:

- low-level embedded software development
- hardware integration

After launch completed:

- commissioning of all new satellites (UK-DMC, NigeriaSat-1, BiSat)
- construction of ground-based testbed for use by NASA Glenn, using engineering model of CLEO.
- development and upload of 'pass-through' software to reconfigure onboard computer to pass frames from CLEO router out to downlink.
 - as an experimental payload, CLEO is not *directly* connected to downlink, although CLEO interconnects a number of onboard computers.
- bringing up ground stations and distributed wide-area network.

Power-on test of the CLEO router on 15 October 2003 showed correct amount of power being drawn; temperatures measured indicated that heatsink was attached correctly. Then left dormant for over six months.

Work after launch: ground-based testbed

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 SSSR and engineering model of mobile router, and networked it from NASA Glenn in Ohio.

Built testbed *after* launch!
Configured CLEO *after* launch!



Virtual Mission Operations Center (VMOC)

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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, planned for launch in 2005, and later TacSat-2. UK-DMC provides an 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!



CLEO and VMOC – meeting needs of participants

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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.



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!

VMOC demo, Vandenberg Air Force Base

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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'.

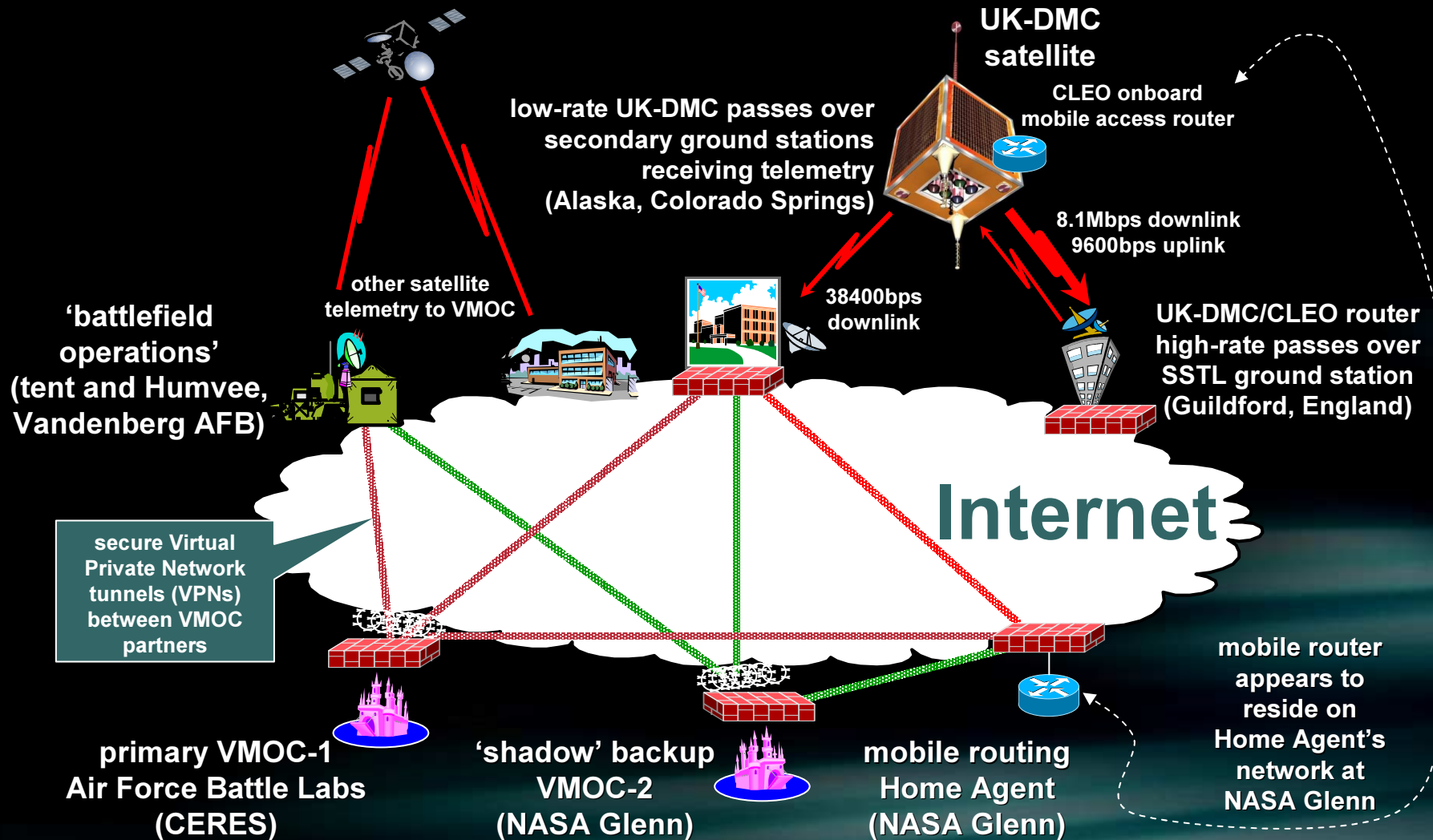
VMOC tent, Vandenberg



Humvee

VMOC demonstration network topology

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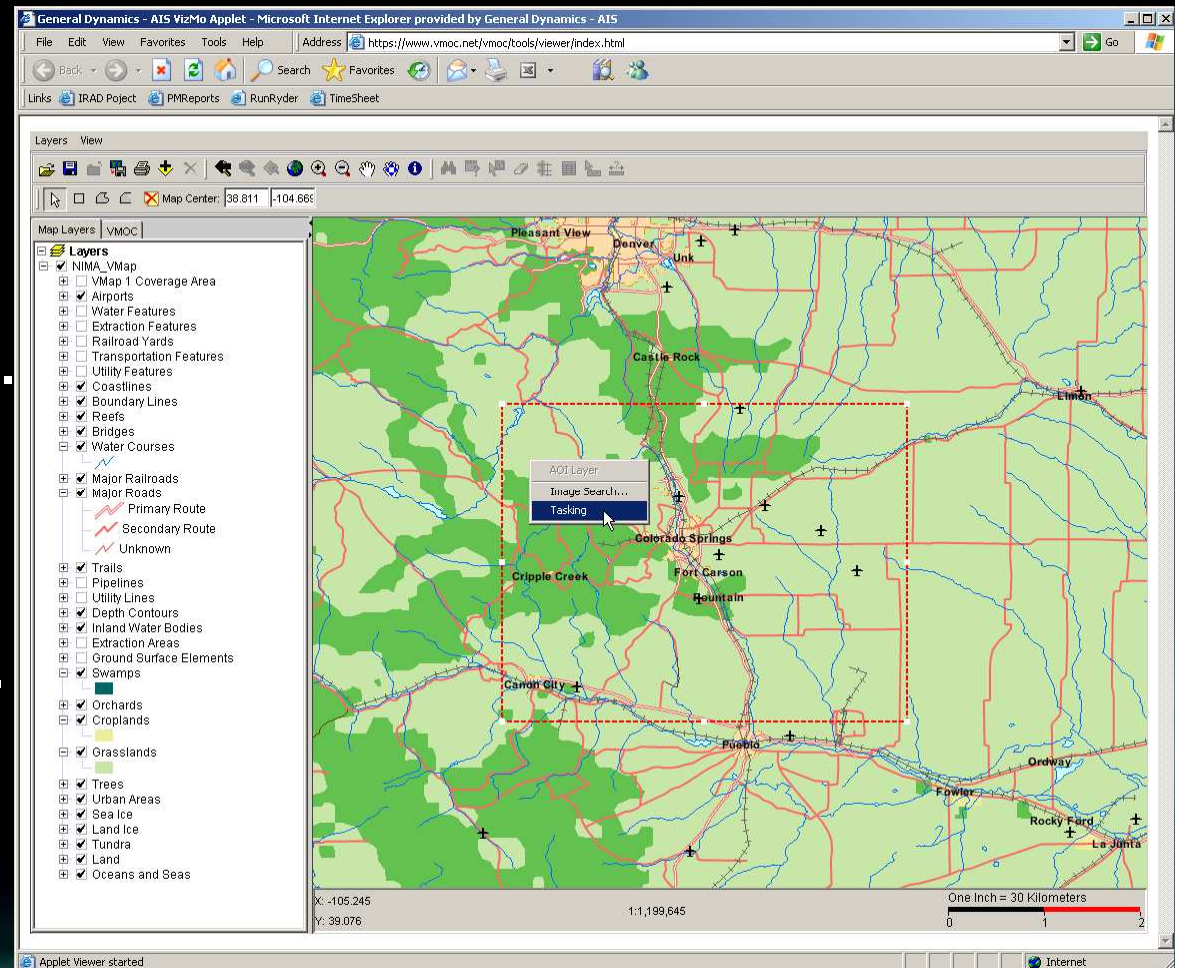
VMOC/CLEO demonstrations to US military

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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.



Tasking to request an image of Colorado

Demonstration involved many organisations

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Acknowledgment of success of CLEO and VMOC

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Computerworld Heroes recognition

GD Technology Award

- **NASA Glenn – Computerworld Heroes finalists**
- **Internal awards in Air Force, General Dynamics and NASA (*Turning Goals into Reality 2005*)**
- **Internal awards for project management**

Some limitations of CLEO

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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 SDRs.

The mobile router is a commercial product, not a space instrument. CLEO does *not* contain 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 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.

Status of CLEO

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CLEO remains operational. As a secondary experimental payload, testing 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 conserve energy.

CLEO has spent two years in orbit. Testing of CLEO has been carried out for over a year, most recently at IEEE Milcom (October 2005).

Timeline of CLEO testing events

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27 September 2003

– UK-DMC and sister satellites launched from Plesetsk.

15 October 2003

– CLEO router power cycled during satellite commissioning tests.

29 April 2004

– CLEO router activated and tested with console access.

May – June 2004

– Testing of VMOC and CLEO from Vandenberg Air Force Base.

14 – 16 June 2004

– First public demonstration of VMOC and CLEO at Vandenberg.

10 May 2005

– Public demonstration to AFEI Net-Centric Operations Conference.

18-20 October 2005

– Public demonstration of CLEO and VMOC at MILCOM 2005.

Other CLEO testing onboard

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GPS – UK-DMC satellite also has onboard a GPS reflectometry experiment. Moving data from the SDR running that experiment to ground requires dedicating passes to that SDR. Data can be moved through the router to be stored on a primary imaging SDR 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. First done October 2005.

IPv6 – CLEO and ground routers are IPv6-capable, but UK-DMC payloads and ground stations use IPv4 only. IPv6 is not yet enabled.

IPsec – CLEO and ground station routers can use this, and could secure unencrypted ground-space link by tunnelling IP traffic through the router. (*ssh* to CLEO is already configured, as is a passworded web interface.) Could also use SNMP and MIBs to show that a satellite payload can be managed just as you would manage a terrestrial network asset.

Beyond the success of CLEO

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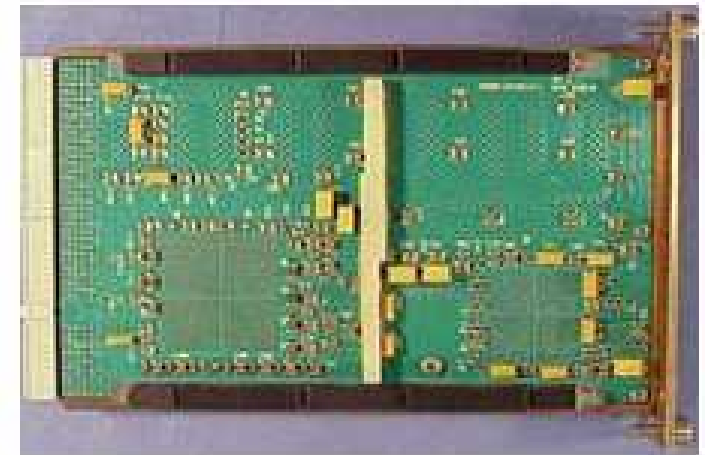
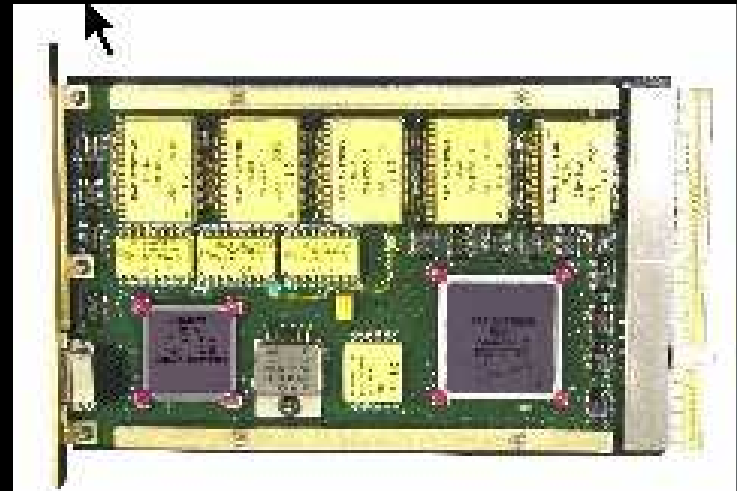
The outcome of the CLEO project and testing has encouraged Cisco Systems to prototype and evaluate IOS software running on radiation-hardened PowerPC processors and hardware very different from this first CLEO demonstration.

Cisco Systems is interested in working with others to take IP and routing functionality to new places... including high altitude and geostationary orbit.

Hardening a router – an experimental prototype

Cisco.com

What might a router running on space-hardened hardware look like?
Took Cisco's IOS. Ported it to run natively on a rad-hardened 133MHz PowerPC processor on a PCI card.
Tested by NASA Goddard in a ground testbed; did double NASA's estimated requirements for Crew Exploration Vehicle. (10,000 pps – still low-end, little optimisation).
But do we *really* need to fully rad harden? What makes sense and is enough for the different space environments at MEO/GEO/lunar?



Thoughts on future satellite connectivity

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Hi-res image downloads are now driving bandwidth demands on downlinks.

UoSAT-12: 312kg, 76.8kbps max downlink (4.1g/bps)

...but with 1Mbps experimental link via Merlion payload (0.31g/bps)
and 10Mbps experimental Ethernet onboard (internally 0.031g/bps)

AISAT-1, UK-DMC: 100kg, 8.1Mbps (0.012g/bps)

Beijing-1: 140kg, 40Mbps (0.0035g/bps)

...while a laptop PC is 2.5kg with
54Mbps 802.11g (5×10^{-5} g/bps) and 1Gbps Ethernet (2.5×10^{-6} g/bps)

Onboard networking – what makes sense at high speeds? Spacewire? Firewire? GigEth? Or even USB (for a single master computer)? Flavours of onboard wireless? Is CANbus still useful?

Published and draft papers, news coverage, video:

Cisco engineering:

<ftp://ftp-eng.cisco.com/lwood/cleo/README.html>

here at Surrey:

<http://www.ee.surrey.ac.uk/Personal/L.Wood/cleo/>

**Questions?
thankyou**