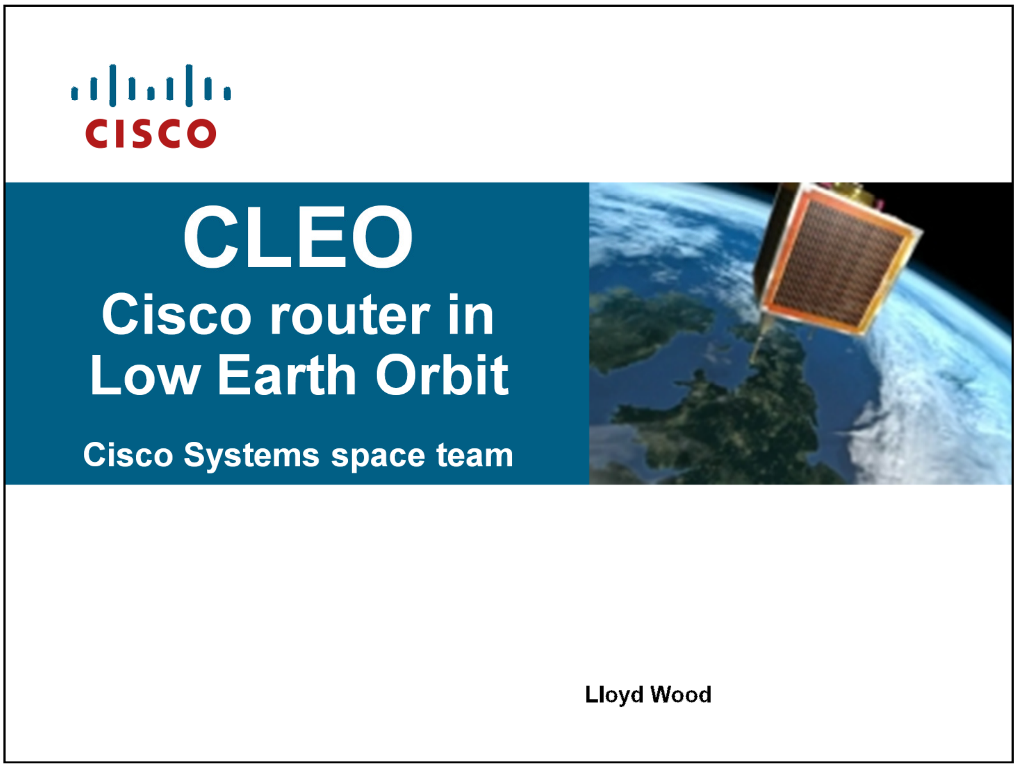


There are notes supporting various slides throughout this slideset.

Several slides have simple animations to gradually reveal further text and related graphics incrementally when clicked in Powerpoint.

These slides are best viewed and printed in colour.

For further information on papers and articles relating to CLEO, and to download Cisco's ten-minute video describing CLEO and the UK-DMC satellite, see:

http://personal.ee.surrey.ac.uk/Personal/L.Wood/cleo/

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.)

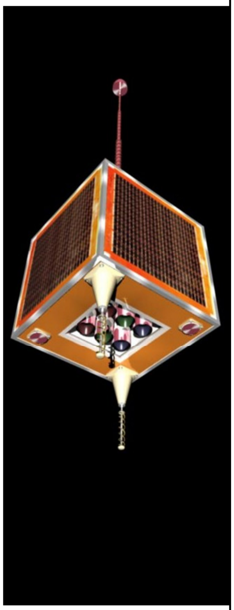
Wired has realized where we could go…

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

This slide is optional and can be omitted for time

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.



The Cisco router is a secondary experimental payload. The other satellites in the Disaster Monitoring Constellation do not have or need Cisco routers onboard – but do still communicate with their groundstations and deliver imagery using IP.

The Vandenberg tests and demonstration tested IP internetworking of the Surrey Satellite Technology satellite imaging system against an IP-based user interface designed for US military use. This demonstrated delivery of images taken by the satellite via IP, monitoring of satellite telemetry also sent over IP, and access to the onboard Cisco router via IP. This showed the worth of Surrey's use of IP to deliver images and for telemetry and command to the US military. It showed the worth of IP for communication of Earth images, and also demonstrated that the Cisco router in orbit worked.

The rendering of the UK-DMC satellite at right shows:

- at top, the stabilising gravity boom for attitude control, with a weight on its tip. This makes the satellite a free-falling pendulum. This is a backup control method; as an imaging satellite, the UK-DMC must be 3-axis stabilised, and also has onboard propulsion.

- on all sides, solar cells. At any one time half of these will be in shadow, giving less power than extended panels that follow the sun (30W.)

- at bottom, S-band antennas and cameras. Six cameras, two in each of three bands pointing either side of nadir but with overlap.

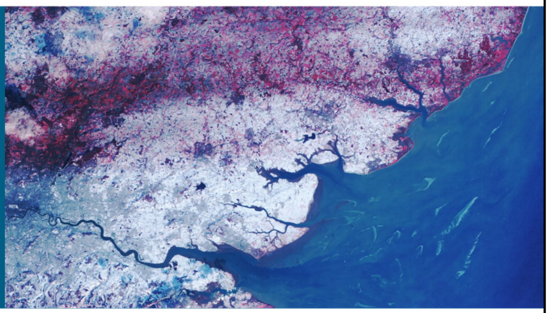
Overview

- 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.

Images shared by other organisations are used with thanks.

Disaster Monitoring Constellation



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Disaster Monitoring Constellation (DMC)

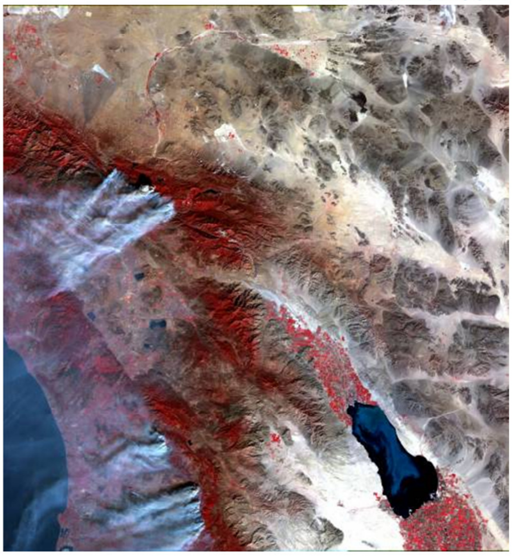
www.dmcii.com

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.



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

DMC resolution can be good enough to determine what's in a farmer's field, to track growth of communities over time where you don't have reliable census data, and even to track the movement of locust swarms.

The Turkish BilSat satellite differs from the usual DMC design in a number of ways, and has a 26m resolution area-array camera for DMC imaging alongside a higher-resolution 12m camera, with onboard JPEG2000 compression. DMC operational frequencies are S-band; BilSat TT&C can use UHF/VHF.

The Chinese contribution to the DMC (Tsinghua-1) has other enhancements, including an extra, high 4m-resolution, camera requiring an additional, faster, X-band downlink in addition to the usual DMC 8Mbps S-band downlink.

More Nigerian DMC satellites, a DMC satellite funded by a Spanish commercial company and a second DMC satellite for the UK have now been launched.

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.

AlSAT-1 launched alongside a Russian Mozhayets navigation satellite.

There were six satellites on the second DMC launch: UK-DMC, NigeriaSAT-1, Bilsat, a Korean scientific satellite, and two Russian educational satellites. Video of the second DMC launch is available as part of the Cisco space video and also in video with the Cisco press release at the time:

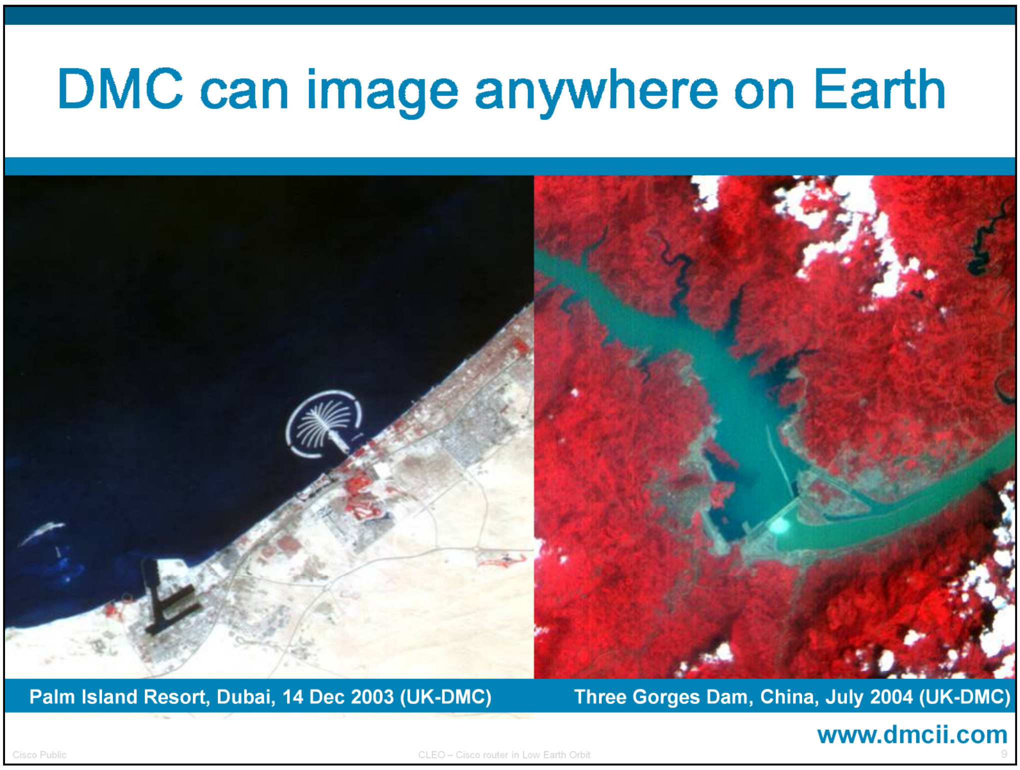
Space No Longer Final Frontier for Cisco Internet Gear, Cisco press release, 26 September 2004. (27 September in Siberia; late on 26th in San Jose due to timezone differences.)

http://newsroom.cisco.com/dlls/ts_092603.html

The Chinese Beijing-1 DMC satellite (previously known as Tsinghua-1, BLMIT-1, and DMC+4 before the final name was chosen) was launched alongside TopSat, a demonstration imaging satellite with 2.5m resolution, built by SSTL and partners for the UK military, SSETI Express for the European Space Agency, and a number of other small satellites.

AX.25 – amateur radio protocol suite based around X.25. 'Amateur X.25'.

UDP – User Datagram Protocol. The lightweight alternative to TCP. Images are transferred by a high-rate reliable transfer protocol built on top of UDP. This protocol, developed at SSTL and called Saratoga and later taken to the IETF in internet-drafts, is intended to fill up the 8.1Mbps S-band downlink while requiring minimal acknowledgements to be sent over the constrained 9600bps uplink.



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These images are closeups of interesting features taken from the much larger 600km-swath width images.

These sample images are from the UK-DMC satellite. As SSTL operates the UK-DMC satellite on behalf of the UK government, SSTL has more latitude to task that satellite to take images of features that are of interest to the general public.

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.

This image is detail from a larger image (inset). See the DMC International Imaging website for more details.

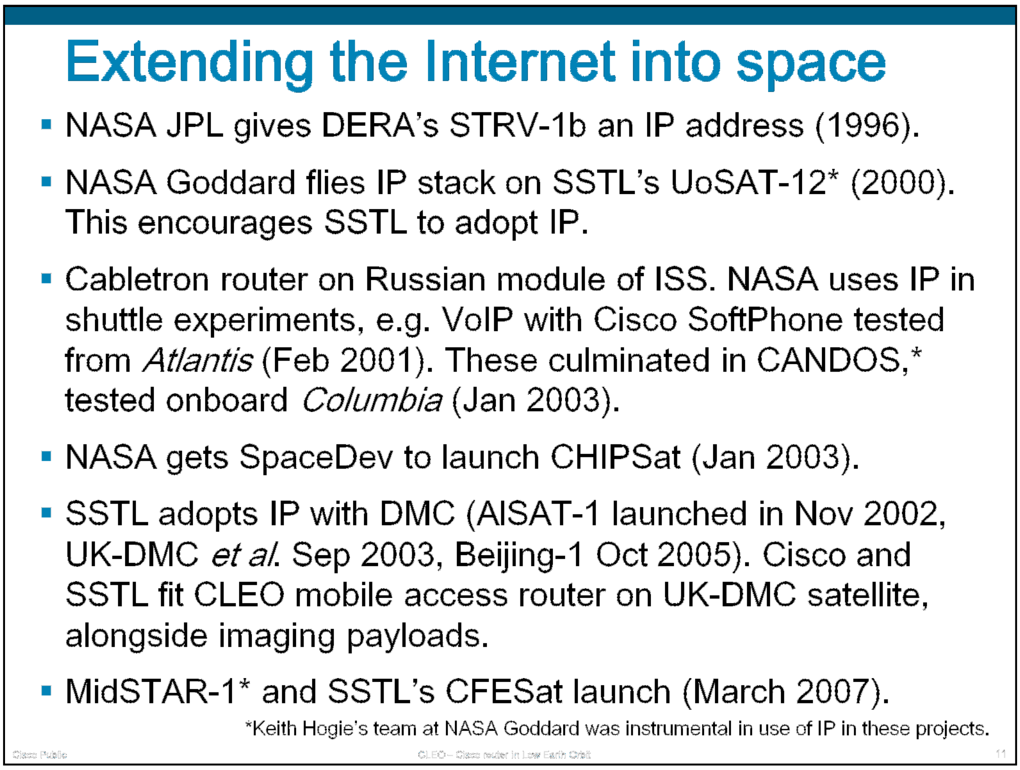
http://www.dmcii.com/

DMC International Imaging is a wholly-owned internal spinoff of SSTL.

Information on the International Charter for Space and Major Disasters is at:

http://www.disasterscharter.org/

A number of space agencies are members of this charter, as is the US National Oceanic and Atmospheric Administration.



The UK Defence Evaluation Research Agency (DERA) launched the Science and Technology Research Vehicle (STRV) satellite in 17 June 1994. IP software was later uploaded and tested.

SSTL's UoSAT-12 (University of Surrey) minisatellite was launched 21 April 1999. An IP stack was later uploaded, giving IP comms in parallel with the AX.25 comms already in use. A Cisco 1601 router was used in the ground station. This was later upgraded to the Cisco 2621s currently used in all DMC ground stations.

NASA developed the Orbital Communications Adapter, which allows the crews of the shuttle and ISS to use IP. This was used with Cisco Softphone experuments on Atlantis in 2001. Communications And Navigation Demonstration On Shuttle (CANDOS) was a payload in the shuttle bay communicating via TDRSS (NASA Tracking and Data Relay Satellite System, which backhauls LEO to ground via GEO bent-pipe satellites). CANDOS used Mobile IP to handle TDRSS handovers and maintain ongoing file transfers. Cisco 2621 routers were used in the ground stations. CANDOS was lost with the seven astronauts aboard shuttle Columbia on re-entry, 1 February 2003. The Cosmic Hot Interstellar Plasma Spectrometer (CHIPSat) is a University-Class Explorer (UNEX) mission funded by NASA, carrying out all-sky spectroscopy of the diffuse background at wavelengths from 90 to 260 Angstrom. CHIPSat was launched 12 January 2003. CHIPSat is using VxWorks onboard on a PowerPC and a TCP/IP stack for IP-based T&C (Telemetry and Command) via S-band links.

CFESat, the Cibola Flight Experiment Satellite, examines radio spectra for ionospheric and lightning studies, using field-programmable gate arrays (FPGAs). As well as science observation, the mission aims to show use of reconfigurable FPGAs to work in the radiation environment of low Earth orbit. The satellite payloads were built by Los Alamos National Laboratory.

MidSTAR-1 was built by the US Naval Academy. It carries the Internet communications satellte (ICSat) experiment.

The networking aspects of many of these IP-based missions are covered in detail in:

K. Hogie, E. Criscuolo and R. Parise, Using standard Internet Protocols and applications in space, Computer Networks (Elsevier), special issue on Interplanetary Internet, vol. 47 no. 5, pp. 603-650, April 2005.

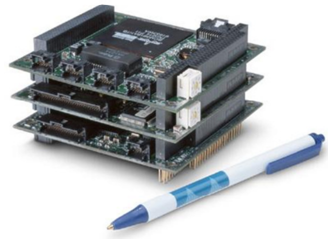
What is the CLEO router?

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.



The most comprehensive paper for a description of CLEO and how it is used, enlarging on this presentation, is:

Using Internet nodes and routers onboard satellites, Lloyd Wood, Will Ivancic, Dave Hodgson, Eric Miller, Brett Conner, Scott Lynch, Chris Jackson, Alex da Silva Curiel, Dave Cooke, Dan Shell, Jon Walke and Dave Stewart, special issue on Space Networks, International Journal of Satellite Communications and Networking, volume 25 issue 2, pp. 195-216, March/April 2007.

See also:

Cisco in space, Phil Hochmuth, Network World, 31 October 2005.

http://www.networkworld.com/news/2005/103105widernetcisco.html

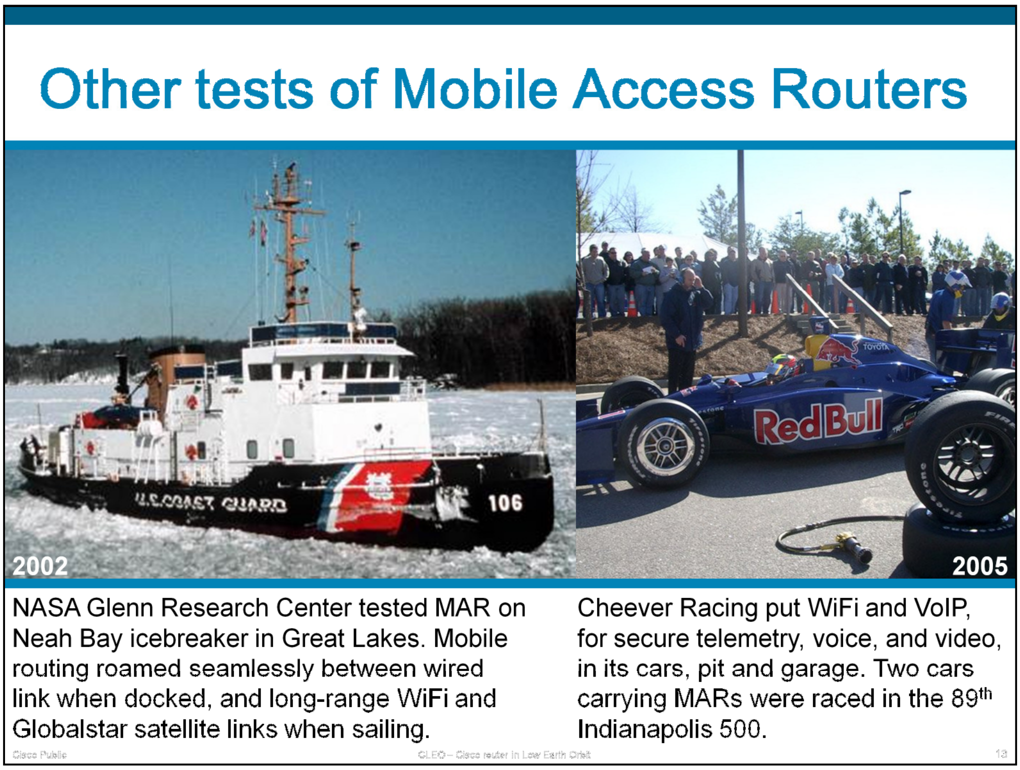
Cisco takes its Internet router to space, Jason Bates, Space News, 19 April 2004.

http://www.space.com/spacenews/archive04/ciscoarch_042104.html

IT's final frontier, Colin Haley, internetnews.com, 5 March 2004.

http://www.internetnews.com/dev-news/article.php/3322471

The 3251 has now been superseded by later additions to the 3200 product family.



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Before working with Cisco to test mobile routing onboard the UK-DMC, NASA Glenn Research Center worked with Cisco to test mobile routing onboard the Neah Bay icebreaker in the Great Lakes. NASA Glenn has Space Act agreements with Cisco Systems and with Western Datacom to share efforts in mobile networking. The Neah Bay trials are described in:

Cisco Systems Joins NASA Glenn Research Center and United States Coast Guard in Development and Deployment of Mobile Networking Solution, Cisco news release, 8 November 2002.

http://newsroom.cisco.com/dlls/prod_110802.html

Technical details in:

W. D. Ivancic, D. Stewart, T. L. Bell, P. E. Paulsen and D. Shell, "Securing Mobile Networks in an Operational Setting", IEEE Computer Communications Workshop (CCW) 2003, Laguna Niguel, California, 20-21 October 2003. Paper available from Will Ivancic's home page:

http://roland.grc.nasa.gov/~ivancic/papers_presentations/papers.html

Cheever placed 22nd and 27th in the Indianapolis 500, Sunday 29 May 2005. (In 2004 Cheever placed 12th and 31st.)

How the Cisco router was fitted to the satellite

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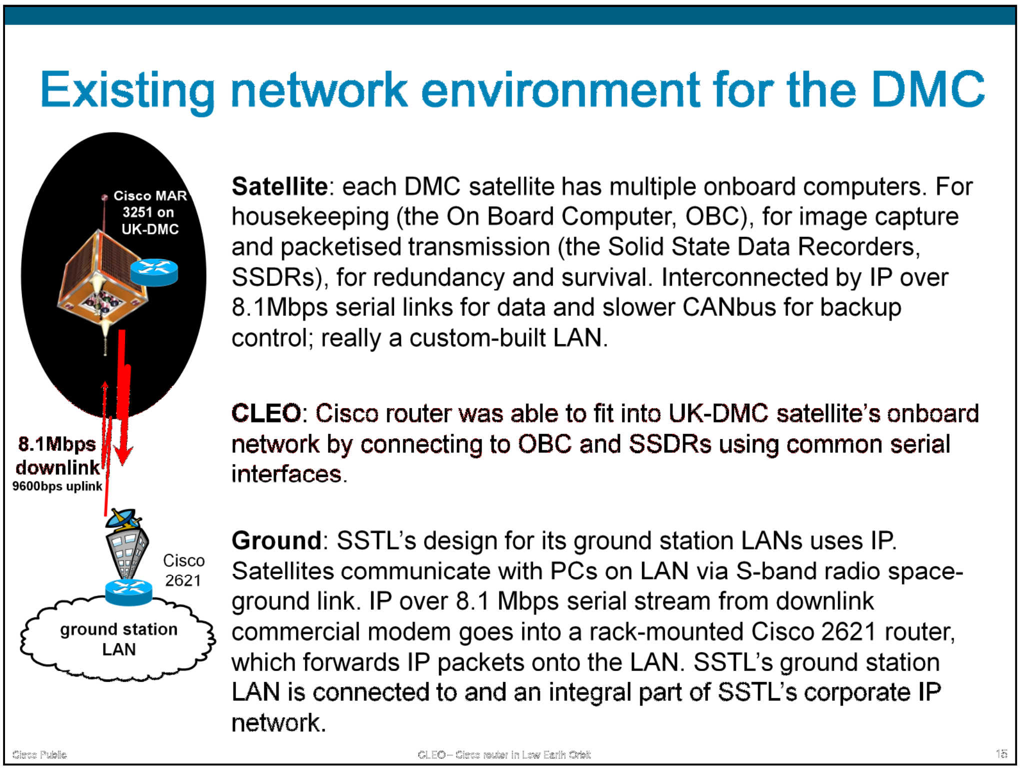


LAN – Local Area Network.

Exact bit rate is 8140800bps. This happens to be 212 * 38400 bps (the low-rate downlink), and also happens to be an integer multiple of the local CANbus speed (at 384kbps).

Serial stream encoding of IP packets is a standard form of HDLC (High-level Data Link Control) with a four-byte Frame-Relay header before each IP packet. This design decision was made for earlier UoSAT-12 IP work with Keith Hogie, and is described in:

K. Hogie, E. Criscuolo and R. Parise, Using standard Internet Protocols and applications in space, Computer Networks (Elsevier), special issue on Interplanetary Internet, vol. 47 no. 5, pp. 603-650, April 2005

The commercial modem used is a Comtech EF Data CDM-600.

More details are in:

Using Internet nodes and routers onboard satellites, Lloyd Wood, Will Ivancic, Dave Hodgson, Eric Miller, Brett Conner, Scott Lynch, Chris Jackson, Alex da Silva Curiel, Dave Cooke, Dan Shell, Jon Walke and Dave Stewart, special issue on Space Networks, International Journal of Satellite Communications and Networking, volume 25 issue 2, pp. 195-216, March/April 2007.

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.

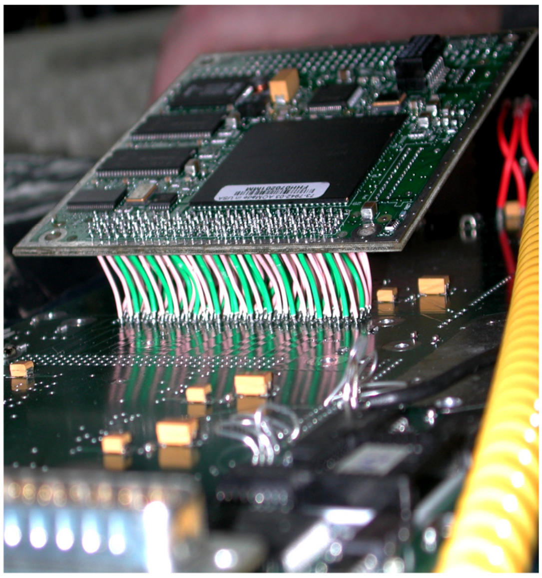
Minor physical modifications made to router and serial card.

• 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.



Space radiation environments vary considerably in harshness and types of radiation. LEO is generally kinder to electronics than higher altitudes, although the magnetic poles and the South Atlantic Anomaly expose LEO satellites to the most radiation they experience.

Being COTS and a commercial product with a list price also avoids US ITAR (International Traffic in Arms Regulations) restrictions that prevent export from US of purpose-built technology.

Tin whiskers growing in a free-fall vacuum have previously caused relays to fail that have led to the loss of spacecraft. NASA’s tin whiskers page has details.

http://nepp.nasa.gov/whisker/

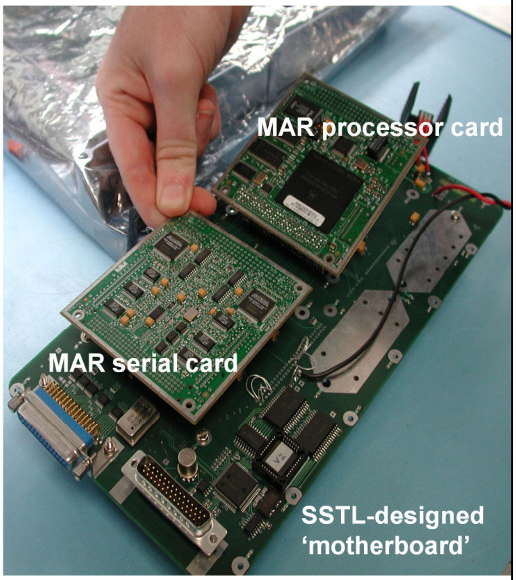
NTP: Network Time Protocol. The CLEO router learns the time from a ground station when it is powered on.

CLEO integration 1 – the router assembly

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

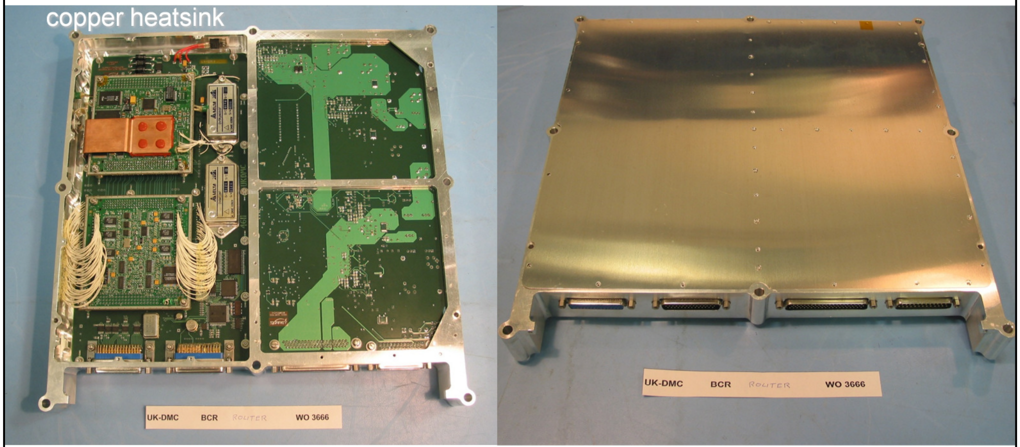
'Motherboard' provides physical mounting, power, serial connections and serial/CANbus interface for access to router console port.

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.

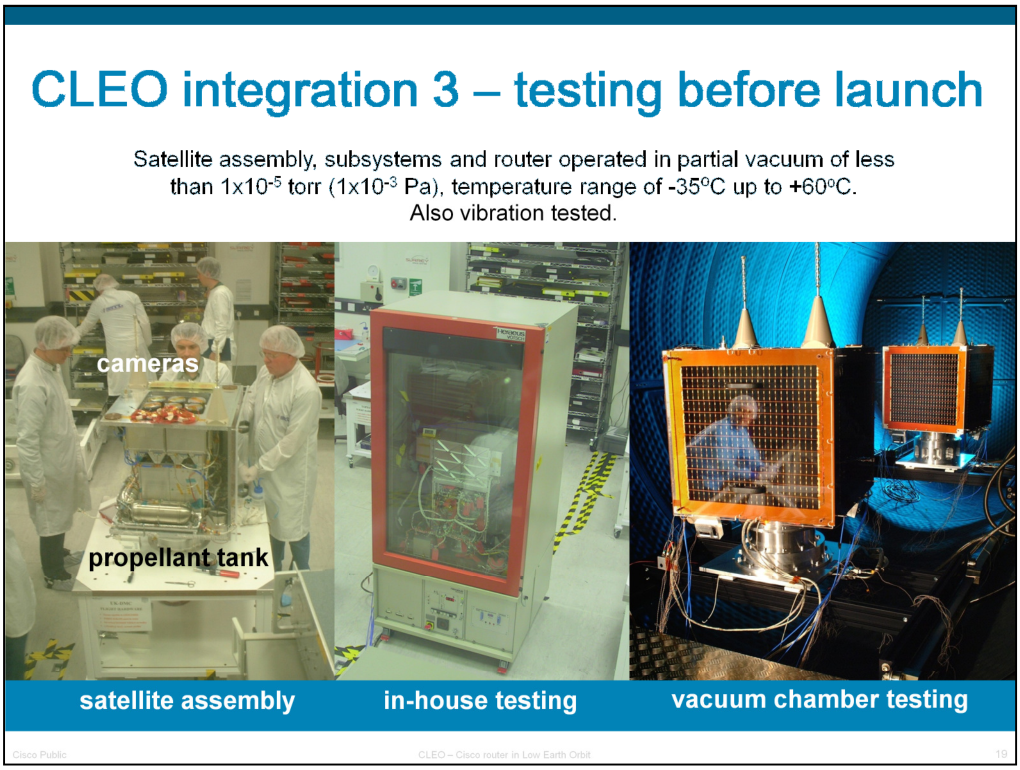


CLEO integration 2 – the payload tray

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.

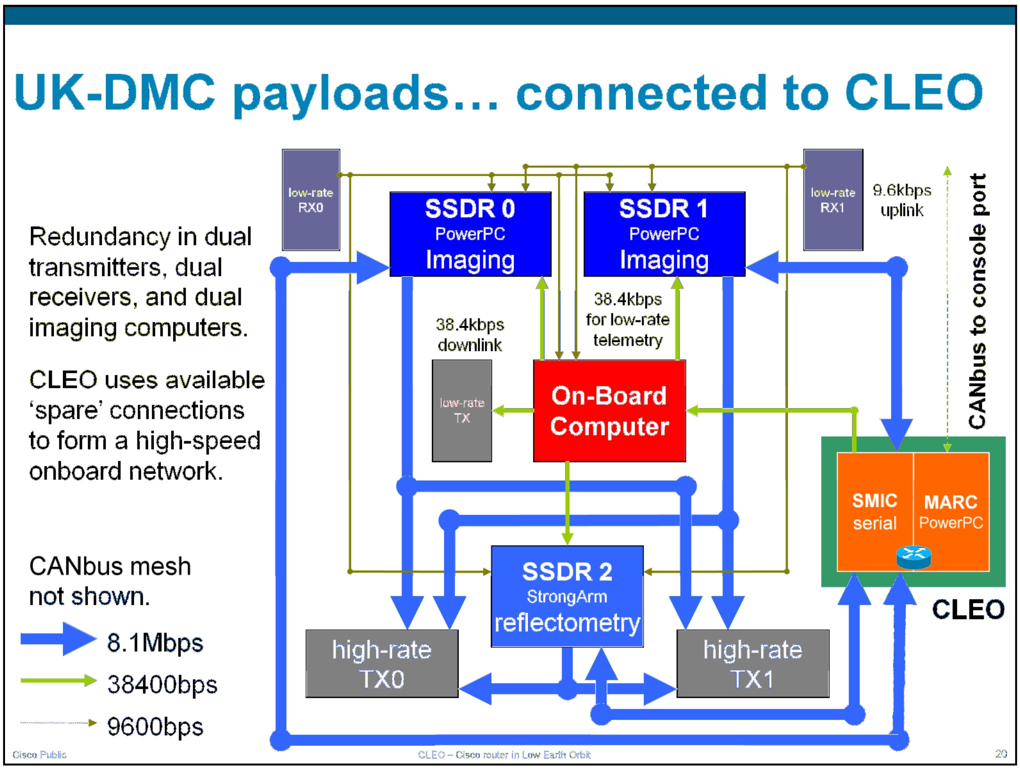


Copper heatsink is visible glued to main processor. Heatsink conducts heat from processor to chassis – in a vacuum and in free-fall, convection using warmed rising air is not possible.



Assembly and in-house testing take place in SSTL's clean rooms on the University of Surrey campus.

Vacuum chamber testing is at Rutherford Appleton Laboratories in Oxfordshire, England; an SSTL press pack photo.



Note that the only way to transfer data at high speed between SSDRs is via the CLEO router. Onboard networking is possible via CLEO; this is being used for GPS reflectometry data transfers, discussed in a later slide.

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.

Twelve minutes is the maximum amount of time a DMC satellite is visible from a ground station. If the DMC satellite does not pass directly over the ground station and is at a lower elevation, the time available for contact is reduced.

Turning CLEO on and off are scheduled events, just like any other future scheduled events, uploaded to the satellite in advance in in text schedule lists to be carried out.

CLEO is running a commercial release of IOS from its onboard flash memory: 12.2(11)YQ (c3200-i11k9-mz.122-11.YQ.bin)

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.

This slide is optional and can be omitted for time.

This testbed is mentioned again later in its new role as a development testbed for Delay Tolerant Networking (DTN).

NASA Glenn had worked previously with Cisco Systems on testing the mobile router onboard the Neah Bay icebreaker. NASA Glenn had also tested the precursor to the VMOC software, Nautilus Horizon (see notes on later slide).

Photos are from near the end of construction; heatsinks and ventilation fans at rear were not yet added.

SSTL had done its own engineering validation with its own hardware assemblies. The ground-based testbed allowed NASA Glenn, who were familiar with the Cisco mobile access router, to get familiar with the existing satellite network environment of the UK-DMC satellite and master configuring the router for that environment. As a result, when given access to the CLEO router onbord the UK-DMC satellite, NASA Glenn were able to use the short time available in ten-minute passes to configure the CLEO router on orbit from nothing as quickly as possible.

VMOC and Vandenberg demonstration

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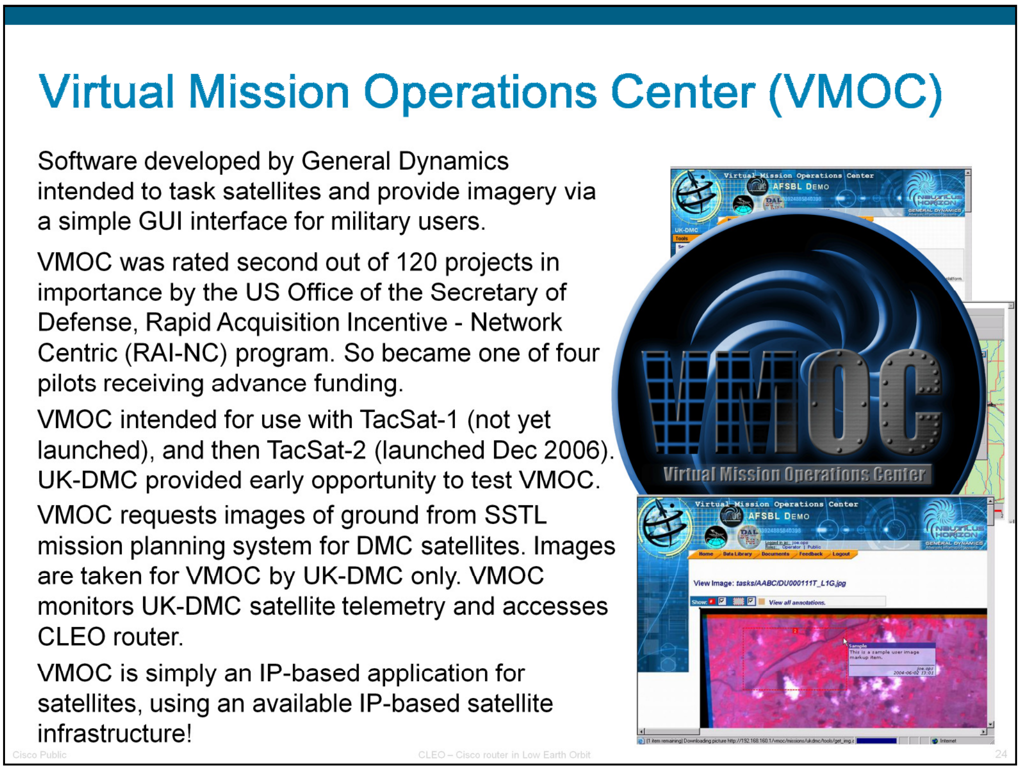


VMOC is a secure knowledge, information and resource management system integrating and presenting the output of other systems, particularly satellites and their supporting infrastructure, and databases of stored satellite imagery.

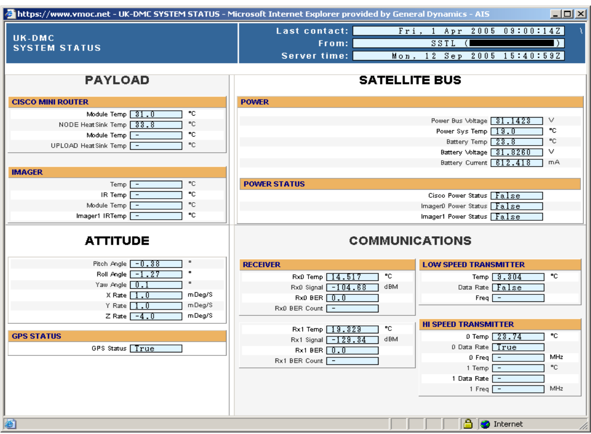
VMOC grew out of an earlier project called Nautilus Horizon. The Nautilus Horizon software was tested by NASA Glenn in 2000:

NASA and Veridian Demonstrate Internet-based Space Command and Control System Architecture, Space Daily, 2 November 2002.

http://www.spacedaily.com/news/internet-00u.html

General Dynamics acquired Veridian in August 2003.

VMOC requests to SSTL mission planning system use SOAP (Simple Object Access Protocol) – an application of XML.



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'.

The use of this large 'in the field' tent and Humvee is somewhat misleading in terms of setup, as all that is required for satellite payload commanding is a laptop, a link to the Internet, and some software.

This testing and demonstration is described in a number of papers and articles available from:

http://personal.ee.surrey.ac.uk/Personal/L.Wood/cleo/

including:

L. Wood *et al.*, CLEO and VMOC: Enabling warfighters to task space payloads, IEEE Milcom 2005, Atlantic City, October 2005.

L. Wood *et al.*, Using Internet nodes and routers onboard satellites, special issue on Space Networks, International Journal of Satellite Communications and Networking, volume 25 issue 2, pp. 195-216, March/April 2007.

W. Ivancic *et al.*, 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.

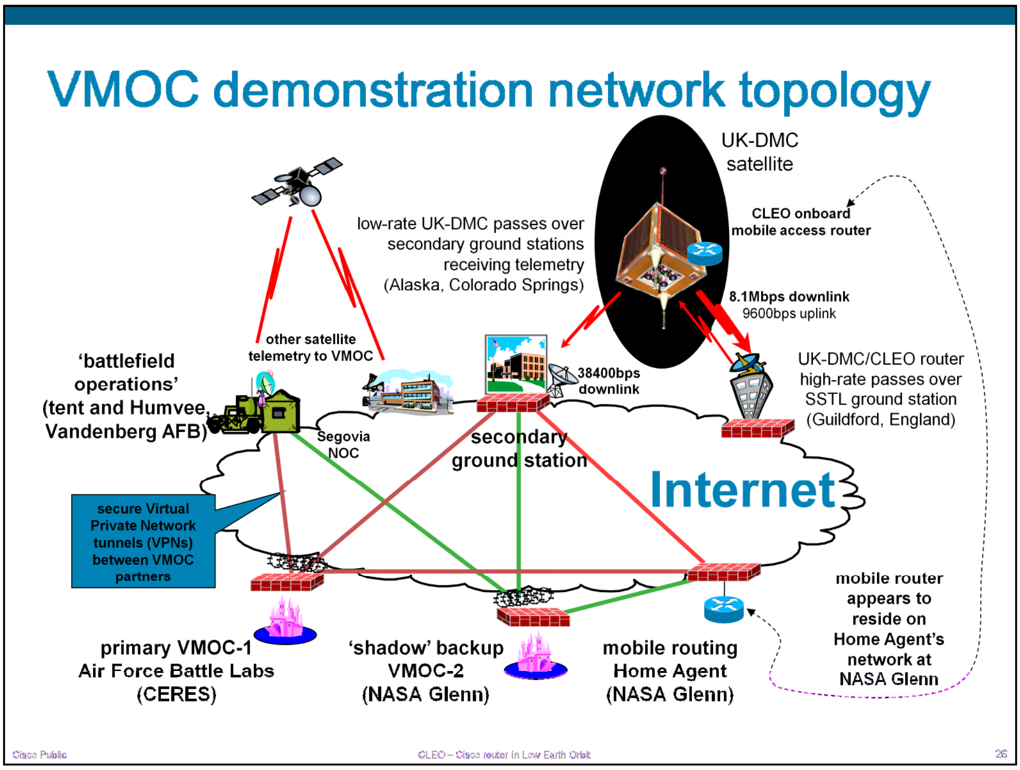
B. P. Conner *et al.*, Bringing Space Capabilities to the Warfighter: Virtual Mission Operations Center (VMOC), paper SSC04-II-7, 18th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August 2004.

Cisco Systems Is At the Forefront of Extending the Internet into Space, Jenny Carless, Cisco news story, 30 June 2004. http://newsroom.cisco.com/dlls/2004/hd_063004.html

Keeping troops virtually in the loop, Henry S. Kenyon, Signal, Armed Forces Communications and Electronics Association (AFCEA) magazine, August 2004.

VMOC: Military eyes in the sky, Janene Scully, The Lompoc Record, 16 June 2004. Also published as Seeking the shortest distance, Janene Scully, Santa Maria Times, 16 June 2004.

14AF, Space Battlelab demonstrate satellite capabilities using Internet, Space and Missile Times, Vandenberg Air Force Base, 11 June 2004.



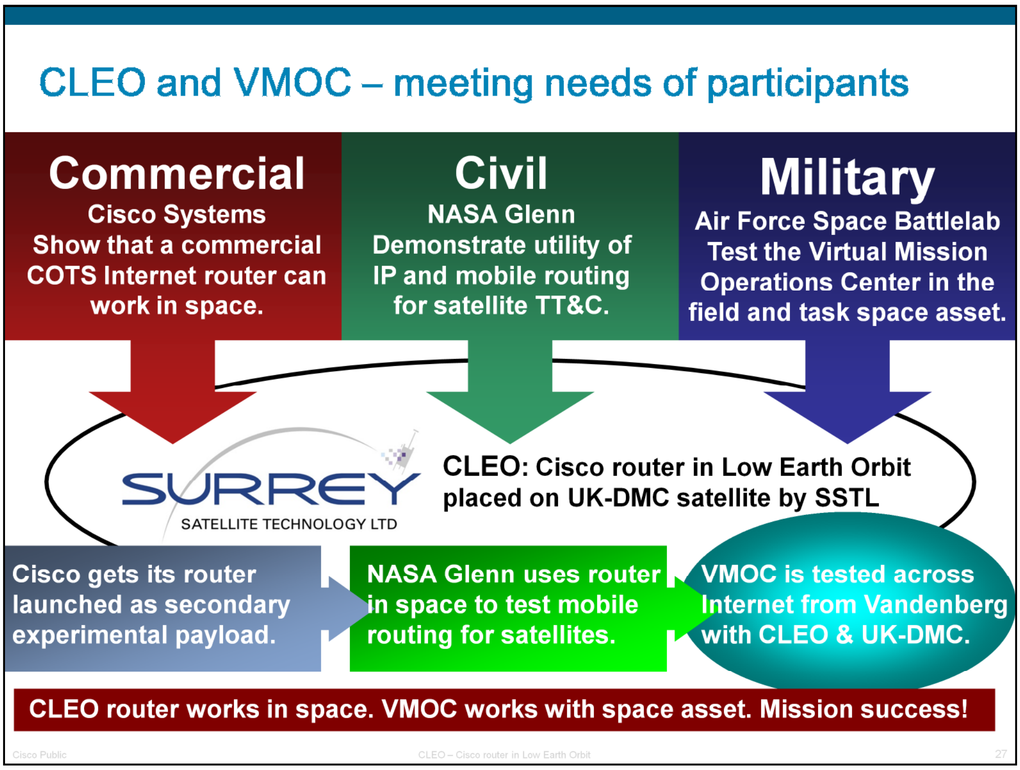
SSTL did not join the VMOC VPN, though it opened access through the SSTL corporate firewall for select VMOC use to request imagery and for mobile routing tunnels. Cisco Systems has donated a number of PIX firewalls to SSTL for use in wide-area networking of the DMC ground stations.

Passes where VMOC accessed the CLEO router were carried out over SSTL in Guildford. These passes also downloaded imagery requested by the VMOC to the ground station, for later notification and pick-up by VMOC.

Passes over the Universal Space Networks ground station in North Pole, Alaska and the Army Space and Missile Defense Battle Lab station in Colorado Springs received additional low-rate broadcast telemetry on the health of the UK-DMC satellite and communicated it across secure tunnels to VMOC. The Alaska ground station was later upgraded to handle the high-rate 8.1Mbps downlink. IP-based telemetry is sent in-band on any available downlink.

The CLEO onboard router was accessed via the mobile routing Home Agent at NASA Glenn. The Home Agent is permanently connected, although CLEO and the UK-DMC satellite are not. NASA Glenn also housed the 'flatsat' ground-based testbed, other 'virtual flatsat' mobile access routers for experimentation, and a 'shadow' VMOC application.

As well as requesting new imagery from the UK-DMC via SSTL's mission planning system, the VMOC could access NASA's Earth Observation Database for stored imagery.


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!
Cisco Public
CLEO – Cisco router in Low Earth Orbit
27

Civil organisations involved in this demonstration:
NASA Glenn Research Center (NASA GRC) – mobile networking experts. (using Space Act agreements with Cisco Systems and Western Datacom.)
Commercial organisations involved in this demonstration:
Cisco Systems – CLEO router, funded integration work with SSTL.
Surrey Satellite Technology Ltd (SSTL) – DMC satellites, imaging support.
General Dynamics Advanced Information Systems (GD-AIS) – did VMOC.
Integral Systems – transportable antenna; also ran pared-down VMOC.
Universal Space Network – Alaska ground station providing telemetry.
Western DataCom – HAIPE encryption for Humvee WiFi link; expertise.
US Military organisations involved in this demonstration:
Air Force Space Battlelab (AFSB) – VMOC program manager for US DoD.
Air Force Research Lab (AFRL) – to experiment with VMOC and TacSat-2.
Army Space and Missile Defense Battle Lab (SMDBL) – set up equipment at Vandenberg and provided telemetry via Colorado Springs ground station.
Space and Missile Systems Center (SMC) Det 12 / CERES – alternate VMOC site and satellite operations centre.
Naval Research Lab (NRL) – will experiment with VMOC with TacSat-1.
Air Force Information Warfare Center (AFIWC) – network security.
14 Air Force (14AF) – at Vandenberg. Maj. Gen. Hamel was primary DoD sponsor of VMOC.
30 Space Wing (30SW) – at Vandenberg. Provided sundry support.
United States Strategic Command CL18 – helped define utility of VMOC.
DoD Chief Information Officer (CIO) – sponsor of VMOC.
Rapid Acquisition Incentive – Net Centricity (RAI-NC) – funded VMOC.

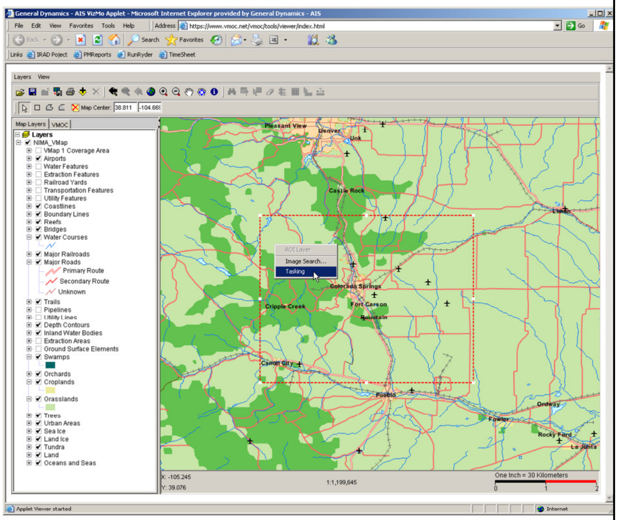
Other demonstrations to US military

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

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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.

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Cisco Systems nominated NASA Glenn Research Center to the 2005 Computerworld Heroes awards for its work on extending the Internet into space in testing the CLEO orbiting router. NASA Glenn became one of 162 Laureates and one of 48 Finalists for these awards. NASA Glenn was one of three finalists in the Science category, won by the European Southern Observatory. Will Ivancic and Phil Paulsen of NASA Glenn and Dan Shell, formerly of Cisco Systems (left photo, from left) attended both the Laureate ceremony in San Francisco (3 April 2005) and the final awards in Washington, DC (6 June 2005).

NASA Glenn and VMOC partners also received internal NASA 2005 TGIR (Turning Goals into Reality) awards for Partnerships for National Security, as a result of enhancing technology development and transfer through partnerships with the US DoD and other US agencies (25 October 2005). Rick Sanford, Cisco space team director, is pictured holding the award at right.

The work on demonstrating VMOC with CLEO garnered internal awards within General Dynamics, where the VMOC application was developed, winning the General Dynamic Advanced Information Systems President's Technology Award (1 April 2005) and the General Dynamics Technology Excellence Award (5 May 2005). Eric Miller of General Dynamics is shown holding the award.

The Air Force Space Battlelab VMOC team was nominated by Air Force Space Command for an internal Air Force Chief of Staff Team Excellence Award. Captain Brett Conner of the Air Force Space Battlelab, who was the project officer for VMOC, was recognised as the Gen. William "Billy" Mitchell Air Force Battlelab Project Officer of the Year for 2004.

Lloyd Wood of Cisco Systems received an internal Outstanding Achievement award from the Global Defense, Space and Security group for coordinating the overall CLEO and VMOC work.

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.

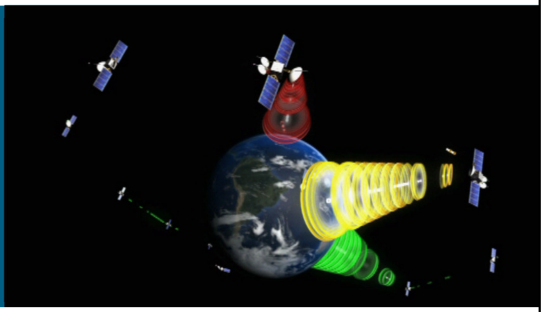
CLEO has now been in orbit for over five years. CLEO and UK-DMC have both exceeded the planned satellite design lifetime. Operation of CLEO has continued over four years.

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

Work with CLEO has been summarised in:

Investigating operation of the Internet in orbit: Five years of collaboration around CLEO, Lloyd Wood, Will Ivancic, Wesley M. Eddy, Dave Stewart, James Northam and Chris Jackson, IEEE Communications Society Satellite and Space Communications Technical Committee newsletter, vol. 18 no. 2, pp. 10-11, November 2008.

Further developments



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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.

GPS reflectometry involves a passive sensor measuring existing GPS signal backscatter from ocean waves, in an attempt to determine wave height, wind speed, and the local environment. This is distinct from active radar techniques that generate radio pulses and measure their reflections.

A third onboard SSDR controls the GPS reflectometry experiment and stores the data from that experiment. To download the data, that SSDR has to be given access to the multiplexer, and packetised data has to be pumped out over the wireless link to ground during a pass.

That third SSDR is an older design based on an older StrongARM-based processor, and can't output data faster than ~3Mbps, so downlink and pass time is not used efficiently. Transferring the data before a pass to the faster PowerPC-based SSDR-1 or SSDR-2 (controlling the imagers) means that less pass time is spent doing experimental data transfers, that the SSDR-3 does not have to be powered up storing data until a pass or at the same time as the high-speed downlink, and that SSDR-1 or 2 can downlink images as well as the GPS data much faster – an overall power/time efficiency saving for the satellite, and simplifying scheduling during a pass. CLEO is turned on for a thirteen-minute period at a time before a pass to allow this data transfer to take place.

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.

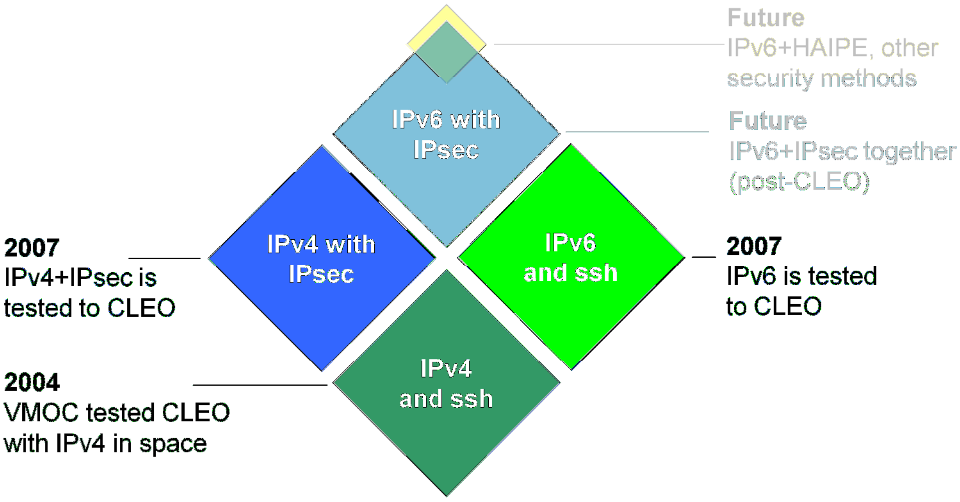
IPsec – CLEO and ground station routers can use this to secure unencrypted ground-space link by tunnelling IP traffic through the router. (*ssh* to CLEO and a passworded web interface were configured in 2004.)

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.

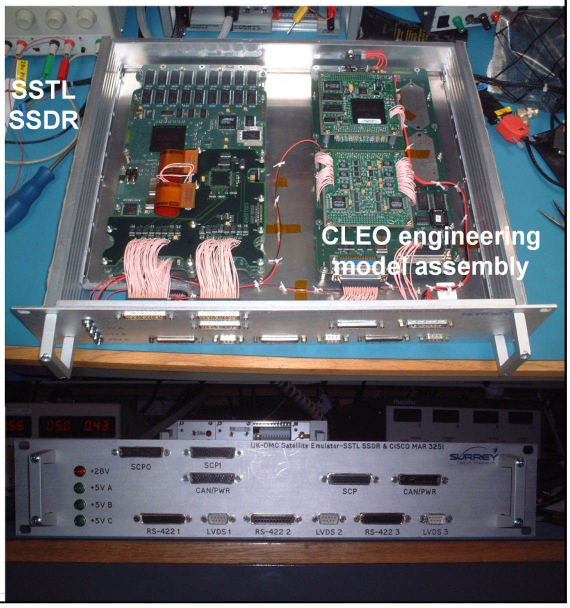
- For rest of world outside US:

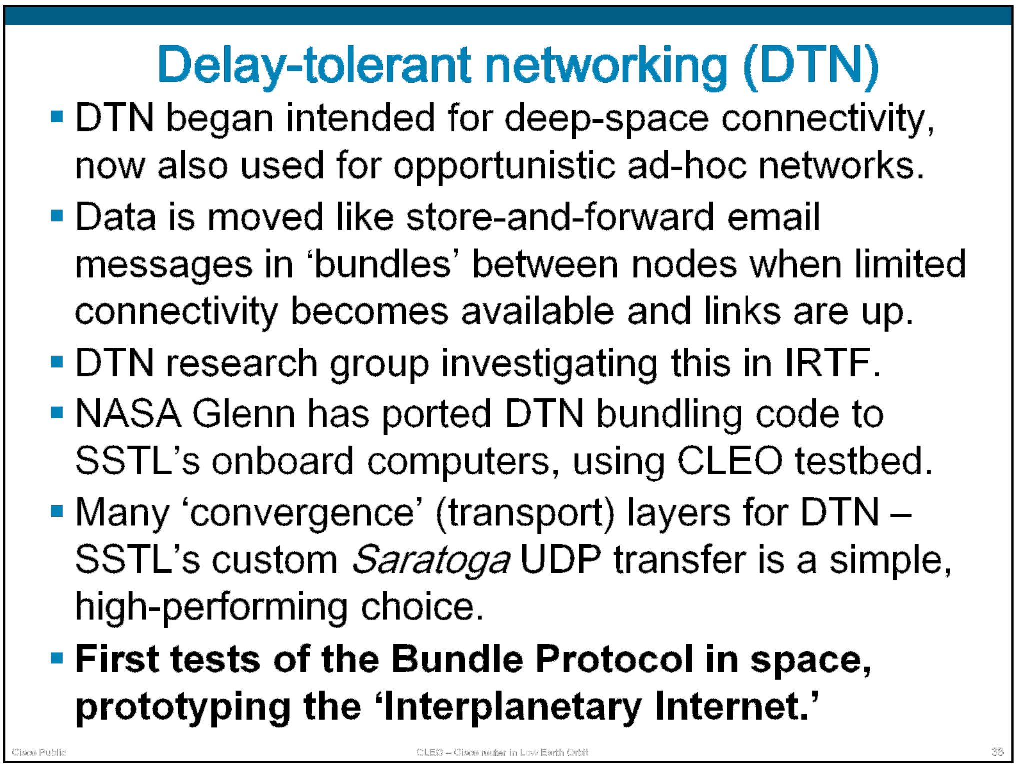
  Owning enough address space and manageable routing tables in the backbone are key here.

  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.





Details of the first tests of the Bundle Protocol from space are in:

L. Wood, W. Ivancic, W. M. Eddy, D. Stewart, J. Northam, C. Jackson and A. da Silva Curiel, "Use of the Delay-Tolerant Networking Bundle Protocol from space," paper IAC-08-B2.3.10, 59th International Astronautical Congress, Glasgow, September 2008.

"UK-DMC satellite first to transfer sensor data from space using 'bundle' protocol," Surrey Satellite Technology Ltd press release, 11 September 2008.

The *Saratoga* protocol and how it can carry the Bundle Protocol have been described and specified in public internet-drafts:

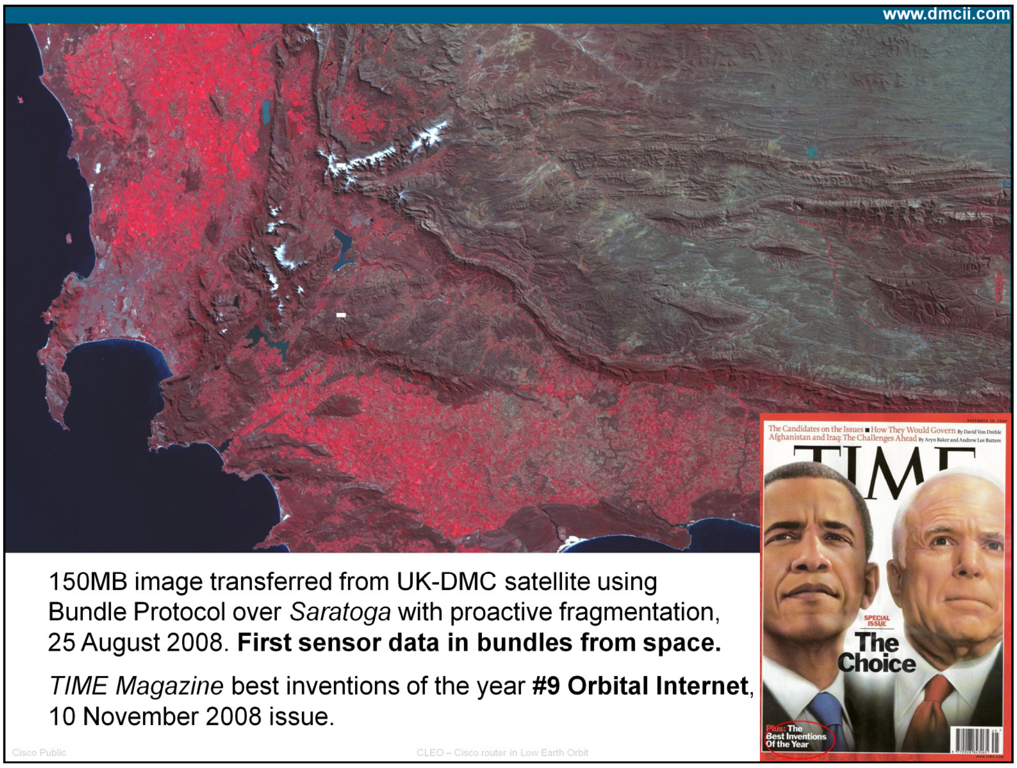
L. Wood, J. McKim, W. M. Eddy, W. Ivancic and C. Jackson, "Saratoga: A Scalable File Transfer Protocol," work in progress as an internet-draft, draft-wood-tsvwg-saratoga.

L. Wood, J. McKim, W. M. Eddy, W. Ivancic and C. Jackson, "Using Saratoga with a Bundle Agent as a Convergence Layer for Delay-Tolerant Networking," work in progress as an internet-draft, draft-wood-dtnrg-saratoga.

Information on Saratoga and the bundles-from-space tests are available from:

http://saratoga.sourceforge.net/

For further information on the Delay-Tolerant Networking Research Group that specifies the Bundle Protocol, see http://www.dtnrg.org/.



TIME's Best Inventions of 2008: #9 The Orbital Internet, Jeremy Caplan et al., Time Magazine, vol. 179 no. 19, 10 November 2008.

CLEO Orbital Internet earns Time Magazine award, Robin Wolstenholme, Surrey Satellite Technology space blog, 14 November 2008.

Interplanetary Internet Passes Test, Alan Boyle, Cosmic Log, MSNBC, 19 November 2008.

“Last summer, the UK-DMC satellite used the protocol to send sensor data down from Earth orbit to a British ground station and onward to NASA's Glenn Research Center in Ohio. That set the stage for October's monthlong deep-space test, involving NASA's Epoxi spacecraft.”

All information on the testing and related drafts (*Saratoga* protocol, how it carries Bundle Protocol):

http://saratoga.sourceforge.net/

Download was via SSTL’s ground station in Guildford, England, then a separate bundle transfer over TCP across the Internet to NASA Glenn.

Bundle Protocol is RFC5050.

Saratoga is defined in

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.

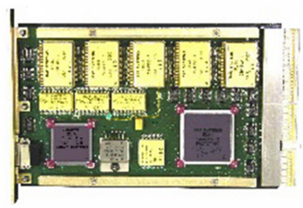
Cisco Systems is interested in working with others to take IP and routing functionality to new places… including high altitude and with **IRIS**, (IP Routing in Space) to geostationary orbit.

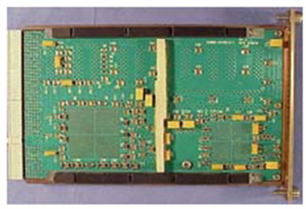
Possible future developments are outlined in:

Daniel Floreani and Lloyd Wood, Internet to Orbit, Cisco Systems Packet Magazine, vol. 17 no. 3, third quarter 2005, pp. 19-23.

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.





Described in:

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, 17-20 October 2005

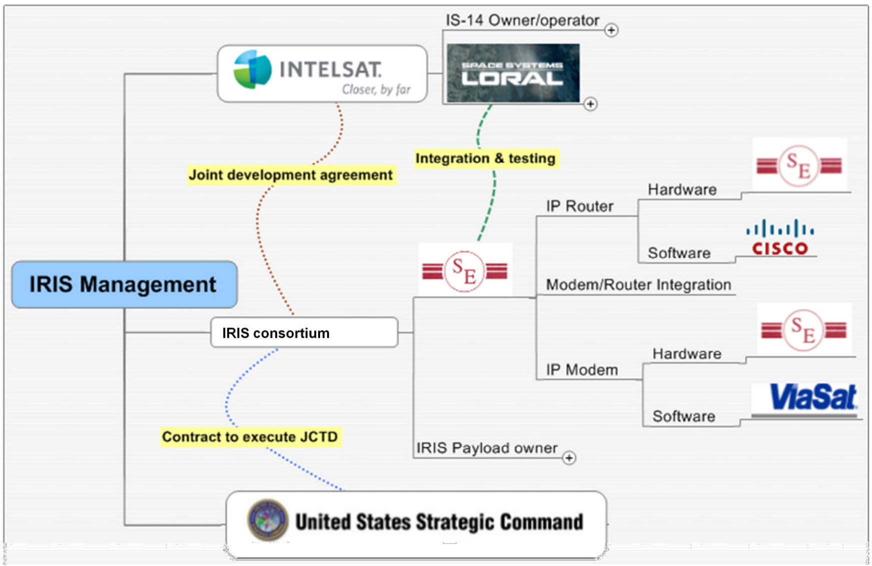
IRIS – IP Routing In Space

- 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.

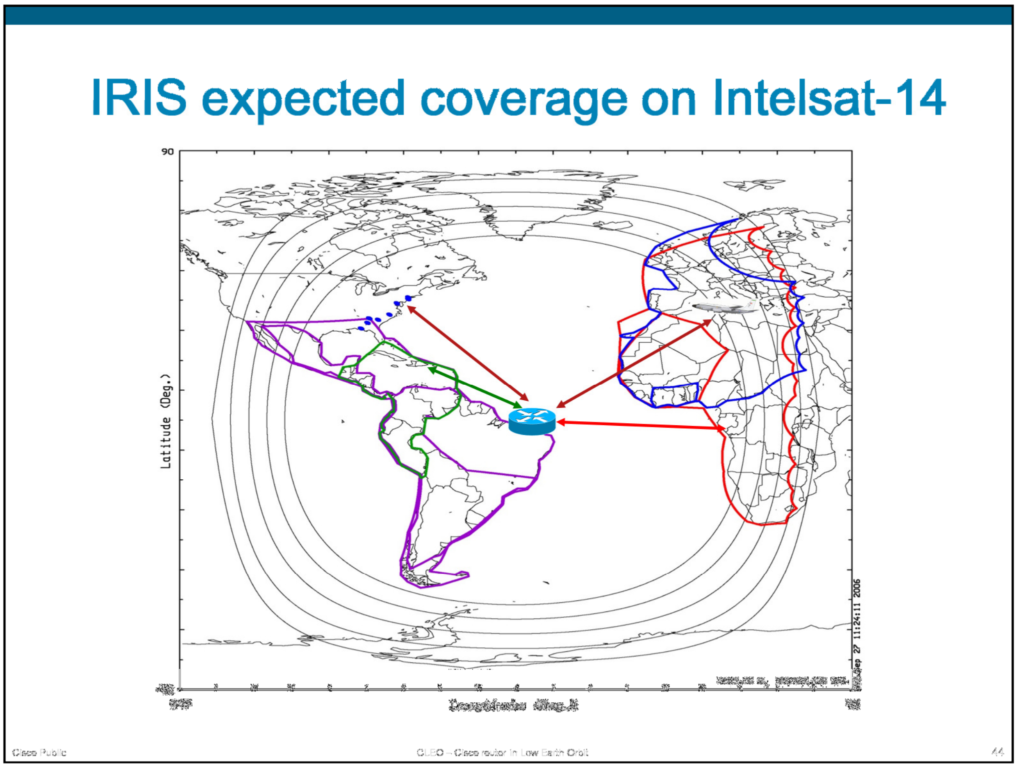
The initial IRIS study was introduced in:
Cisco Pushes Vision of IP-Based Satellite, Ground Systems, Missy Frederick, Space News, 12 June 2006.
Cisco Increasingly Looks to Military Space Projects, Andy Pasztor, Wall Street Journal, 30 May 2006 (Dow Jones), page B3, 31 May 2006 (print).
Stratcom Asks Cisco, PanAmSat To Study Feasability of Adding IP Router to PAS-14, Missy Frederick, Space News, 22 May 2006.

Intelsat has since bought Panamsat.

Partners in IRIS



IRIS hardware development by SEAKR Engineering in Colorado.



This shows C- and Ku-band coverage from the IRIS satellite, and Intelsat Points of Presence (POPs) on the ground.

IRIS will be stationed at 45 degrees West.

further information:

just google “cleo router”

Questions?

thankyou

point of contact for further information on CLEO:

Lloyd Wood (L.Wood@society.surrey.ac.uk)

PC DVD-ROMs of the ten-minute ‘Cisco mobile router tested in orbit’ video can be requested from Lloyd.

For further information on papers and articles relating to CLEO, and to download Cisco’s ten-minute video describing CLEO and the UK-DMC satellite, see:

http://personal.ee.surrey.ac.uk/Personal/L.Wood/cleo/

CISCO