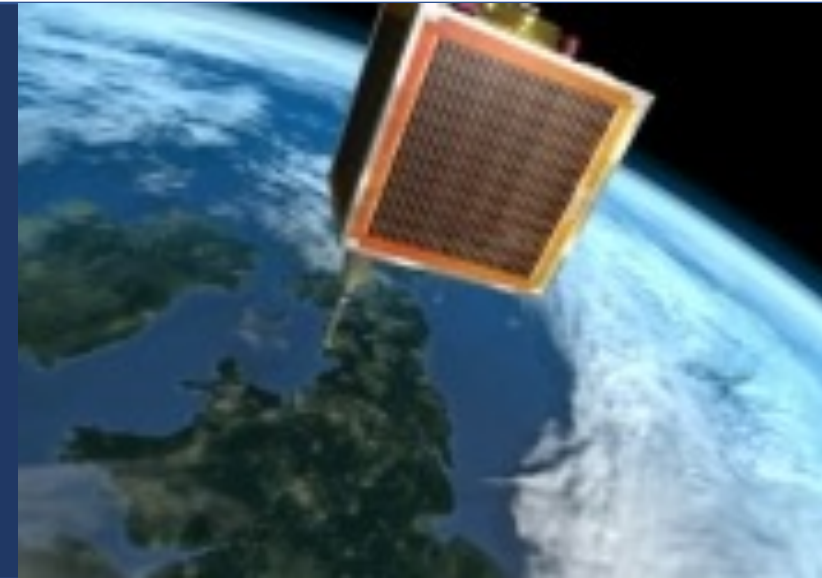


# Building the Interplanetary Internet

Experiments with networking in space  
Involving the UoSAT-12 and UK-DMC satellites



**Lloyd Wood**  
Surrey Space Centre lecture  
Guildford, 8 December 2023

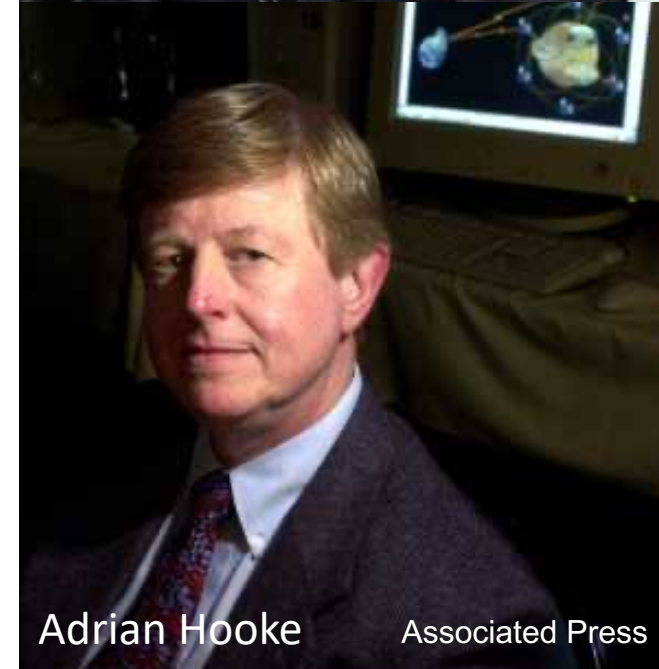
# The Interplanetary Internet (IPN)?

- Vint Cerf announces start of IPN effort twenty-five years ago... in 1998.
- Collaborated with Adrian Hooke of **NASA Jet Propulsion Lab (JPL)** – who led CCSDS (Consultative Committee for Space Data Systems), an ISO subgroup that sets *standards for space*.
- Space probes predate computing; tape-recorder bitstream mindset. Wanted to move them towards packets and networking.
- Long propagation delays are difficult for computers; can't work with existing protocol timers, need patience.



Vint Cerf

Wikipedia

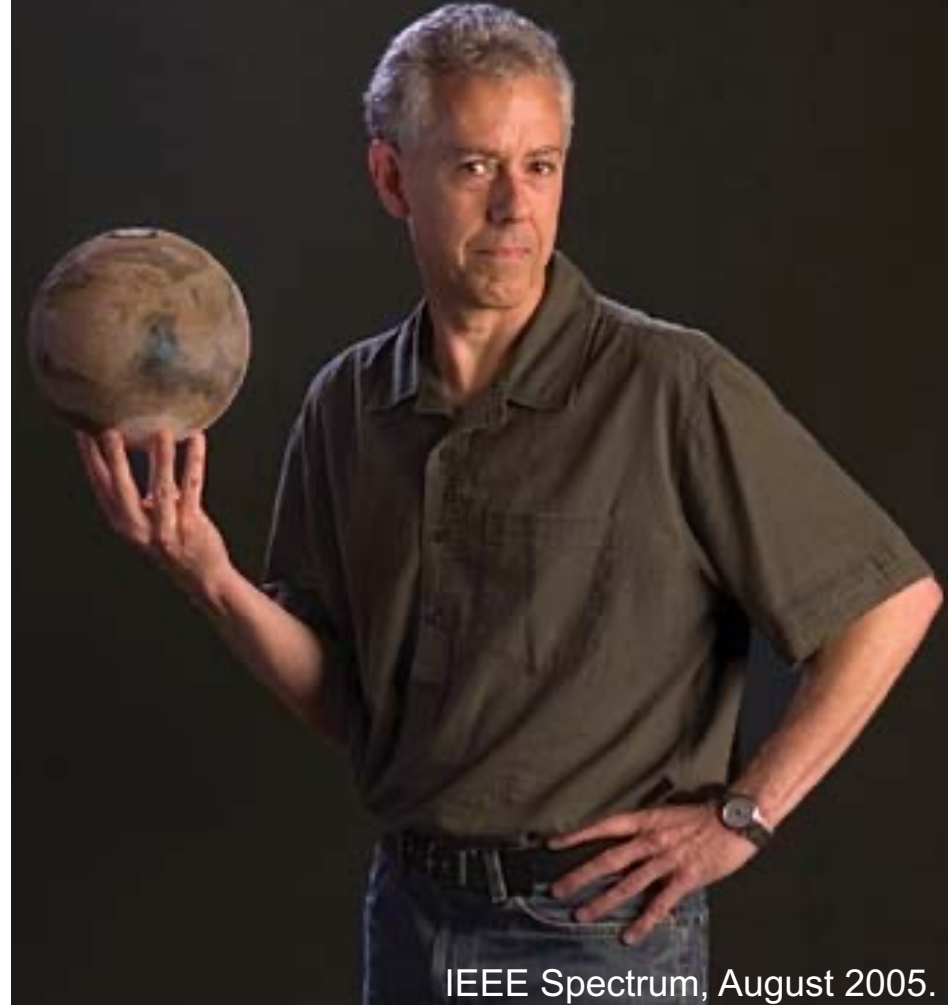


Adrian Hooke

Associated Press

# Scott Burleigh from NASA JPL

- Careful consideration of legacy CCSDS base and slow migration.
- Gave us CFDP, Licklider LTP, and the then-new Bundle Protocol for IPN.
- CCSDS File Delivery Protocol (CFDP) a precursor to the Bundle Protocol – both layer over everything: TCP, UDP, CCSDS, you name it. *Complex*.
- CFDP (lite) in use by *Messenger* Mercury probe and *Deep Impact* (later *EPOXI*) comet mission. Licklider LTP a ‘stripped down’ CFDP in some ways.



IEEE Spectrum, August 2005.

**CFDP**  
**LTP**  
**Bundle Protocol**

**CCSDS**

# Keith Hogie from NASA Goddard

- Found that CCSDS not really layered or modular. Grew tired of reinventing the wheel and reimplementing CCSDS protocols with tweaks.
- Proposed basic standards use – IP in standard Frame Relay over ISO-standard HDLC (High-level Data Link Control). Showed that this worked with Surrey (UoSAT-12) and on final *Columbia* mission (CANDOS STS-107).
- HDLC can also be carried easily over CCSDS, as CCSDS supports ‘tape recorder bitstream’ – easier than CCSDS ways to carry IPv4 (or IPv6). CCSDS is treated as the channel for the HDLC bitstream.



IEEE Spectrum, August 2005.

**Internet suite**

**HDLC/FR/IP**

# SSTL tries a new alternative to good old AX.25...

- UoSAT-12 launched 1999. AX.25 for TT&C.
- Prototyped a lot of new technologies:
  - 1Mbps S-band link (the *MERLION* payload),
  - cameras, Ethernet, stabilisation... some used in the later Disaster Monitoring Constellation.
- ...including an IP stack developed with Hogie at Goddard, fitted over the existing HDLC for AX.25 with a Frame Relay shim.
- Webserver in space! (HTTP transfers)



# Extending the Internet into space

- JPL gives DERA's Space Technology Research Vehicle STRV-1b an IP address (1996).
- Goddard flies IP stack on SSTL's UoSAT-12\* (2000). This encourages SSTL to adopt IP for future missions.
- Cabletron router on Russian module of ISS (HP Procurve switches came much later). NASA uses IP in shuttle experiments, e.g. VoIP with Cisco SoftPhone tested from *Atlantis* (Feb 2001). These culminated in CANDOS, tested onboard last *Columbia* mission (Jan 2003). NASA gets SpaceDev to launch CHIPSat (Jan 2003).
- SSTL adopts IP with DMC. (AISAT-1 launched in Nov 2002, UK-DMC *et al.* Sep 2003, Beijing-1 Oct 2005...). First payloads, then platform. Cisco Systems puts CLEO Internet router on UK-DMC satellite, as secondary payload alongside imaging payloads.
- MidSTAR-1 (Hogie again) and SSTL's CFESat launch (March 2007).

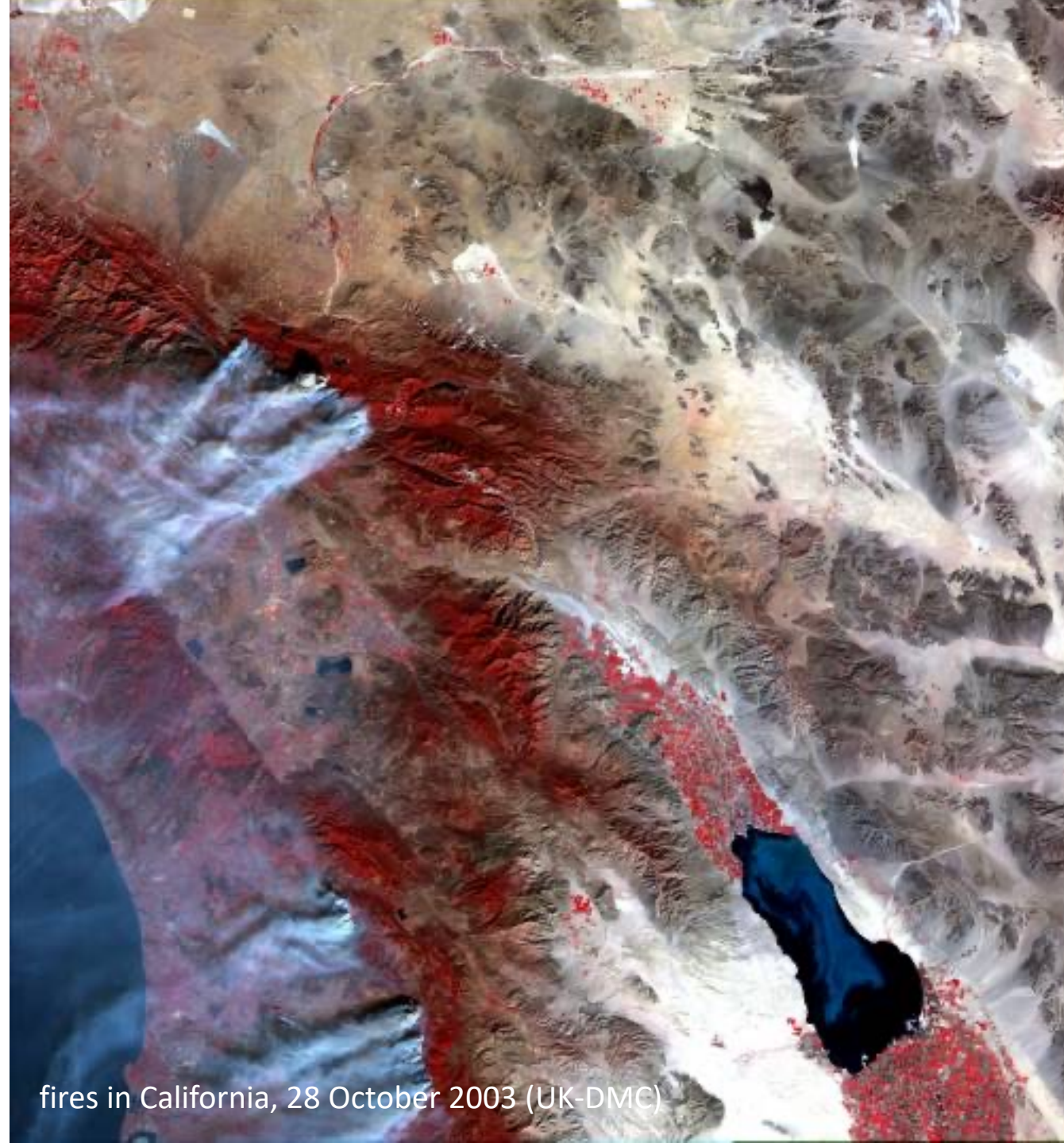
# Disaster Monitoring Constellation (DMC)

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, United Kingdom, Turkey and China. Also commercial.

Each government buys a local ground station and a satellite. Stations networked.



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

# New Orleans

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



## Hurricane Katrina

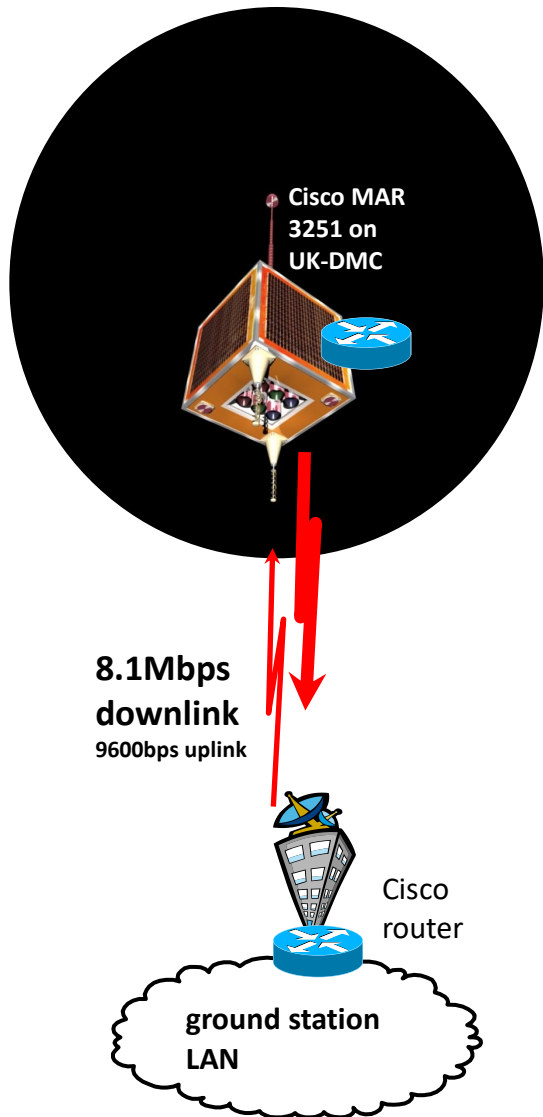
In this false-colour image, dry land is red. Flooded and damaged land is shown as brown.

Small part of an image taken by the Nigerian DMC satellite on Friday 2 September, 2005, 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.

# IP networking environment for the DMC



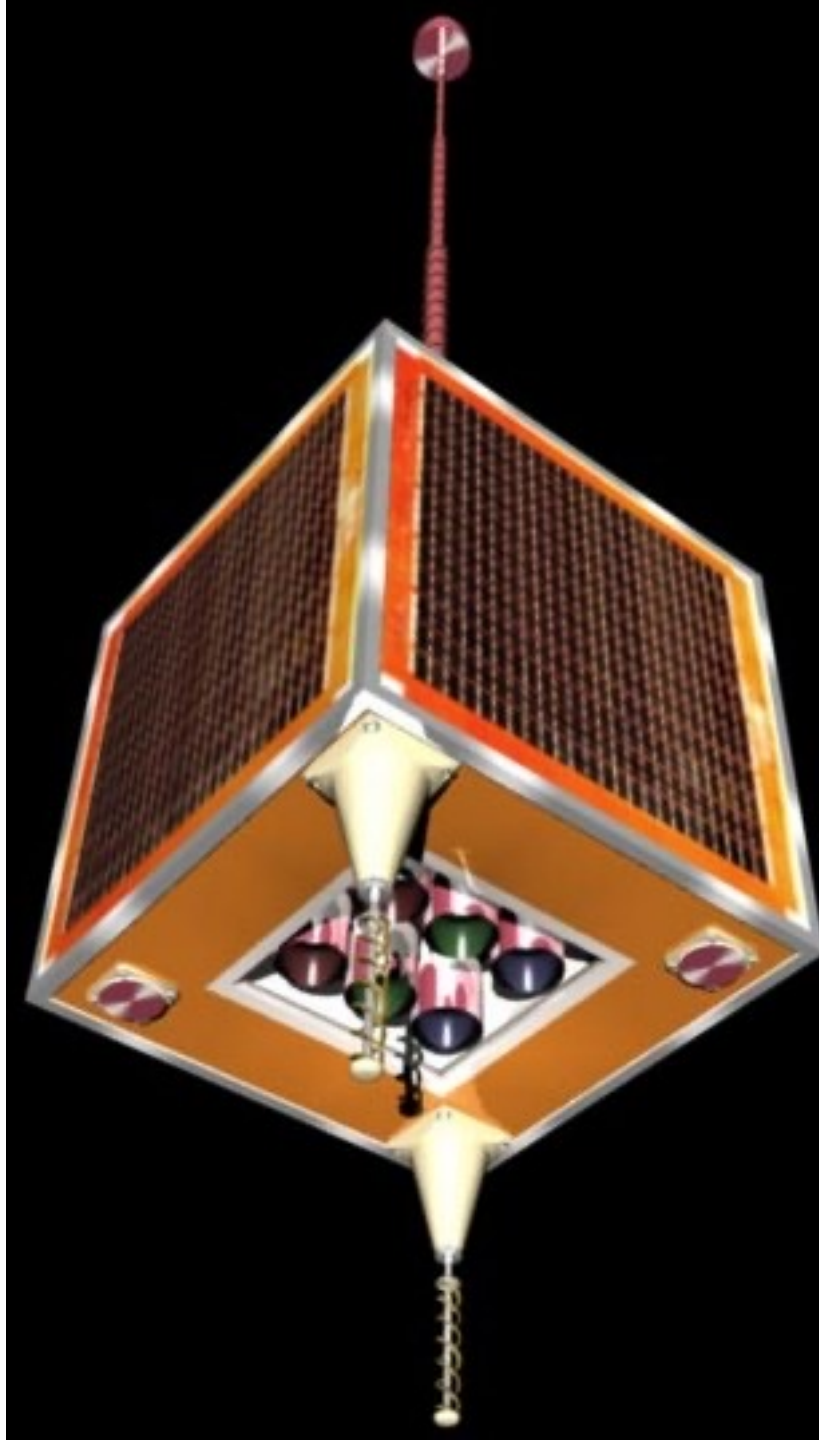
**Satellite:** each DMC satellite has multiple onboard computers. For housekeeping (the On Board Computer, OBC), for image capture and packetised transmission (the Solid State Data Recorders, SSDRs), for redundancy and survival. Interconnected by IP over 8.1Mbps serial links for data and slower CANbus 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 minimum 8.1 Mbps serial stream from downlink commercial modem goes into a rack-mounted Cisco 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. Serial rates much faster on later missions. Images downloaded using a fast UDP/IP protocol: *Saratoga*.

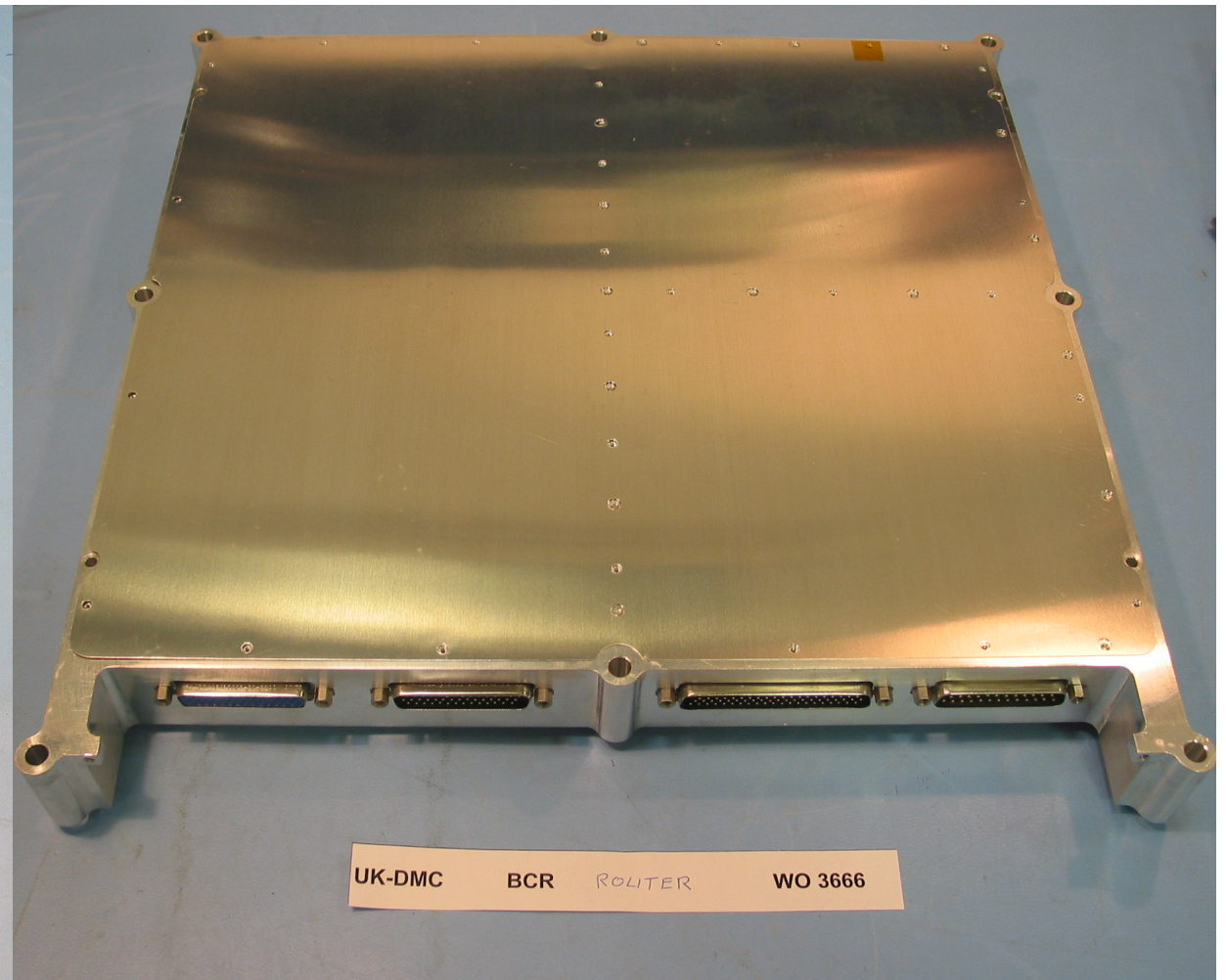
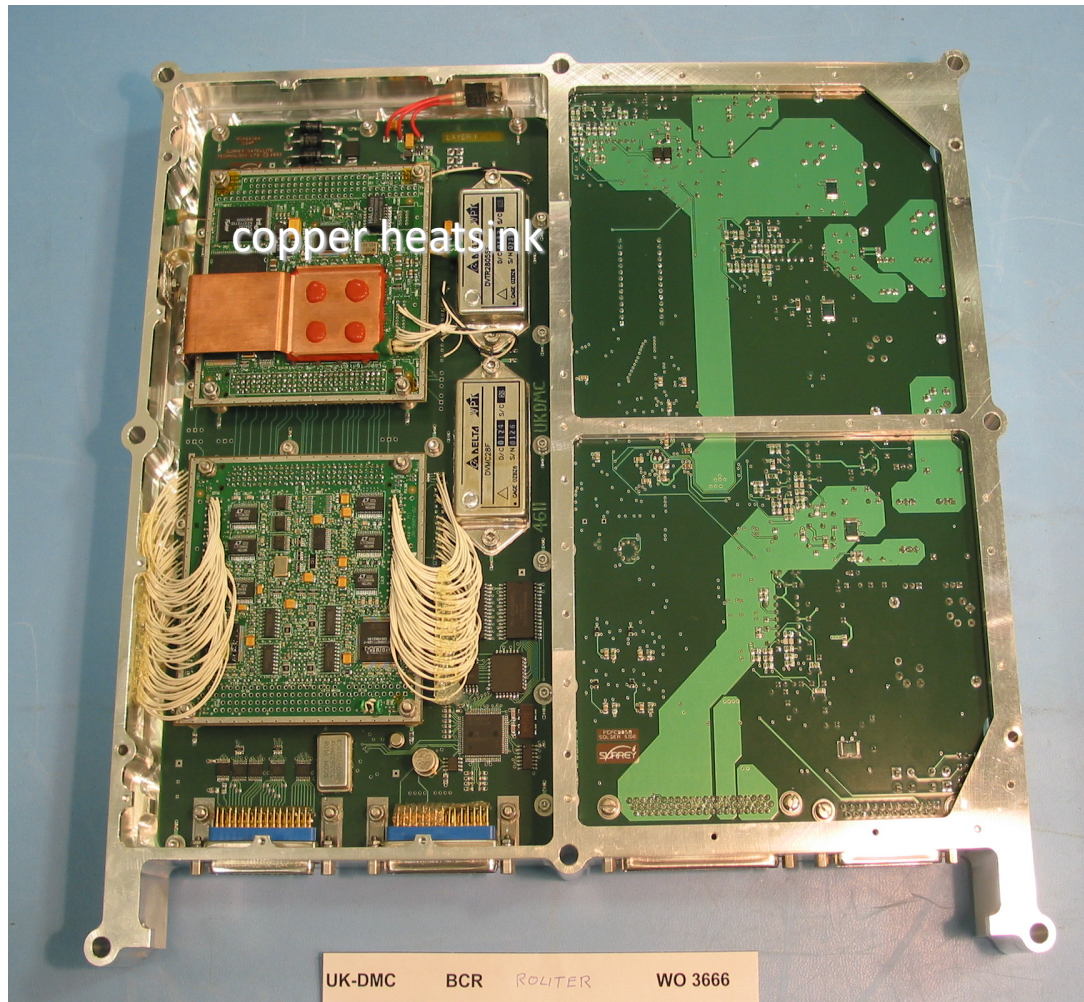
# Testing the Internet in orbit

- 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 of Virtual Mission Operations Center (VMOC) at Vandenberg in June 2004.
- IPv6 and IPsec tested in orbit, March 2007.
- Cisco router worked throughout UK-DMC lifetime.
- Router launched on geostationary satellite (Cisco *IRIS* on *Intelsat-14*, November 2009).



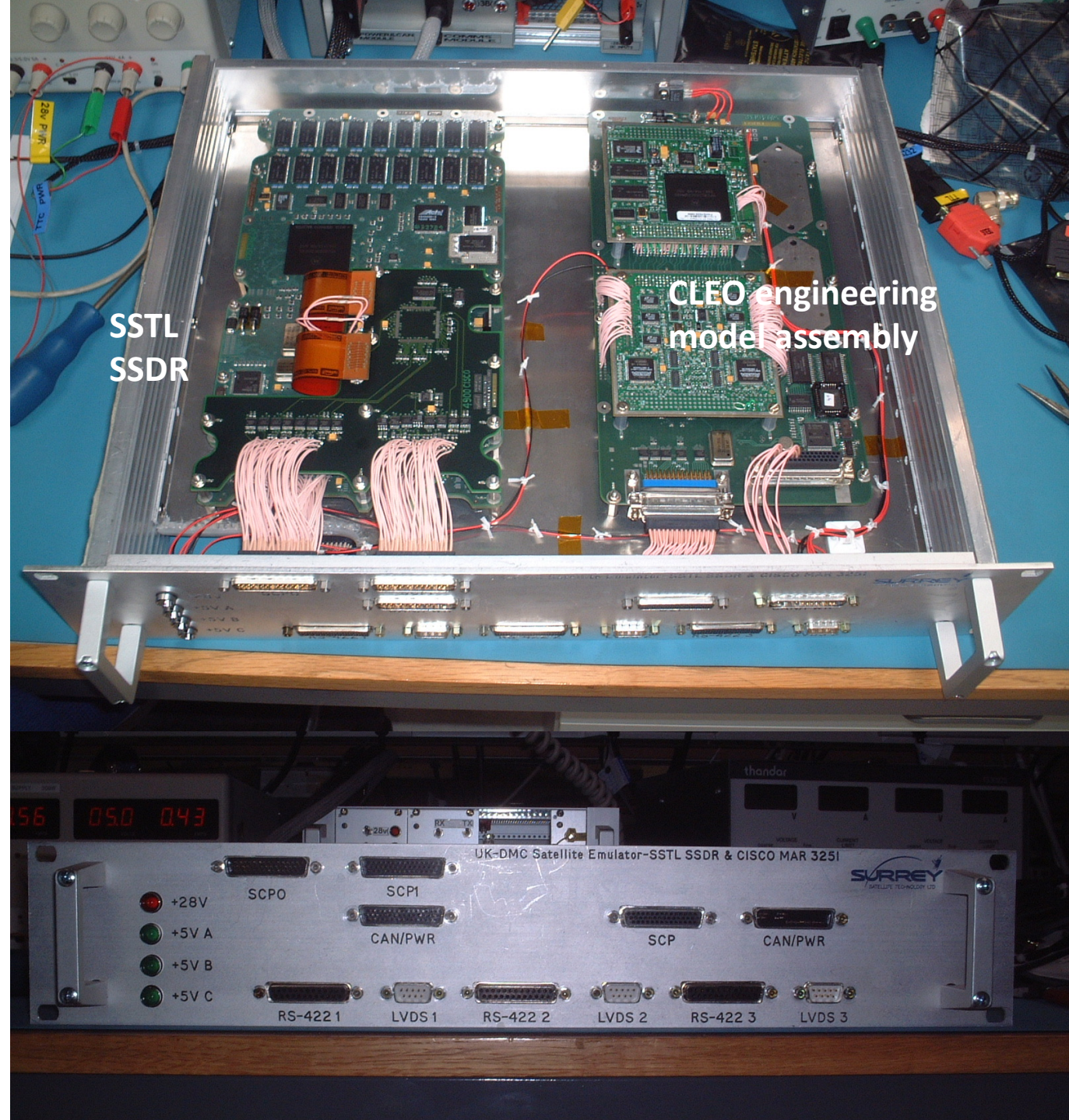
# CLEO Internet router in UK-DMC payload tray

CLEO mobile router and serial card talk to other computers onboard via simple serial links. Possible because of Hogie's serial/HDLC/FR/IP approach allowing integration.



# Ground-based testbed

- 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 then used for software development.
- Delay-Tolerant Networking Research Group's 'Bundle Protocol' put over *Saratoga*.



# Vint sets up an ISOC SIG...

- Internet Society Special Interest Group (IPNSIG).
- Then a short-lived IRTF 'Interplanetary Internet' group (IPNRG).
- Problem scope widens to 'Delay Tolerant Networking' (Kevin Fall in SIGCOMM).
- Initial bundle format created, 2003.
- IRTF DTN research group set up. (Kevin introduces DTNRG at IETF 56, March 2003.)
- DARPA *Disruption Tolerant Networking* proposers' day, January 2004. (Lots of funding.)
- Eventually, an IETF DTN workgroup



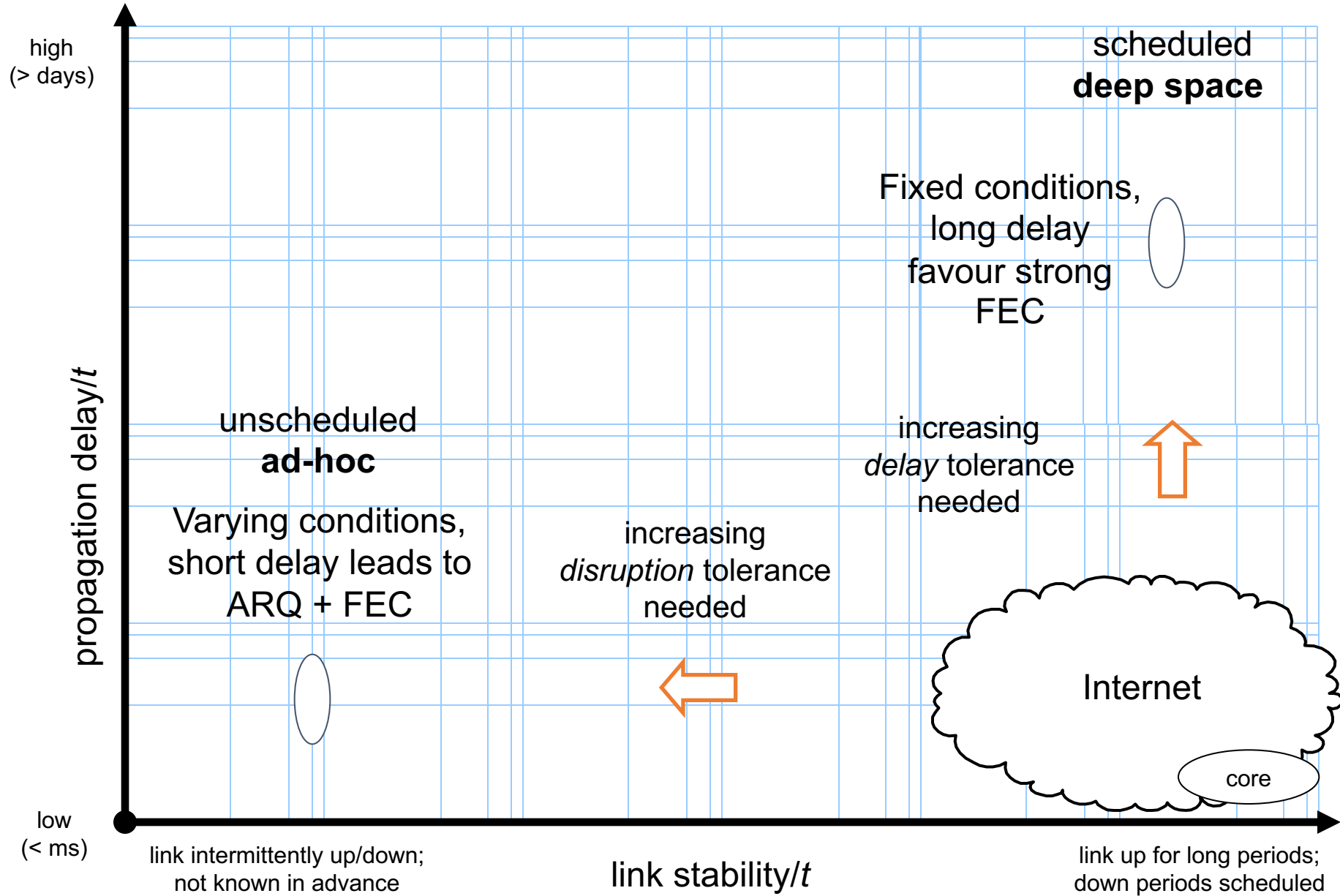
Kevin Fall

Delay Tolerant Networking

# Problem scope was consistently widened

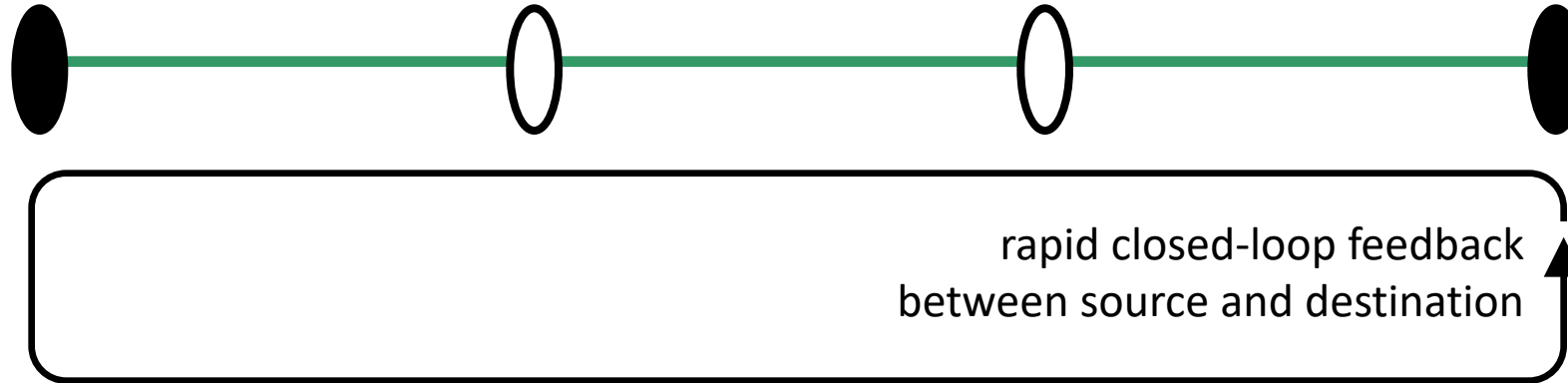
- First, let's solve *interplanetary* networking for the long delays of deep space. IPN!
- Then, let's solve *delay-tolerant* networking for intermittently-connected ad-hoc networks. DTN!
- Then, let's solve *disrupted* ad-hoc military networks under battlefield conditions. Still DTN!
  
- Increased the interest/attention/funding.
- A way for NASA JPL to attract experts and approval, at low cost to JPL – but would it still solve their original problem?

# Two different problem spaces



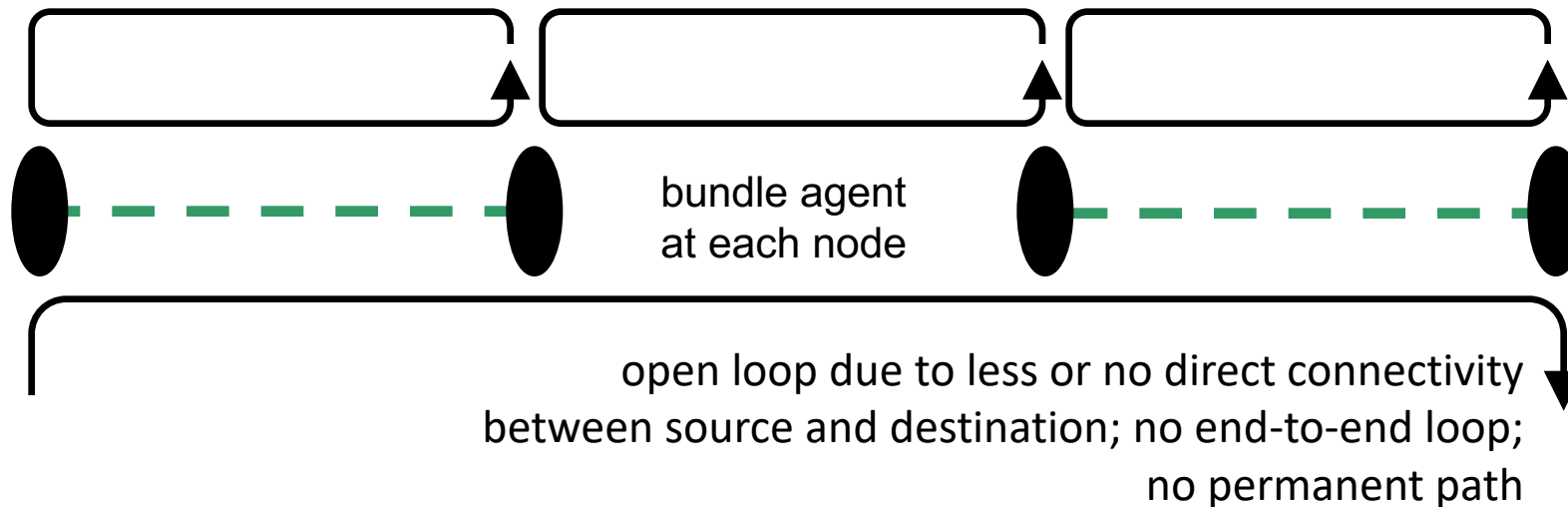
## Terrestrial fixed Internet

little need for resends between or checking at nodes when resends can easily and quickly be done end-to-end over the whole path instead



## Delay-tolerant network

more reliance on separate closed loops between each pair of nodes with local checking for *e.g. custody transfer* and to increase throughput



# What is the Bundle Protocol?

- This layers over different *internets*, just as the Internet Protocol layered over different *networks*.
- Uses ‘convergence layer adapters’ which are responsible for reliable transmission and delivery over each network.

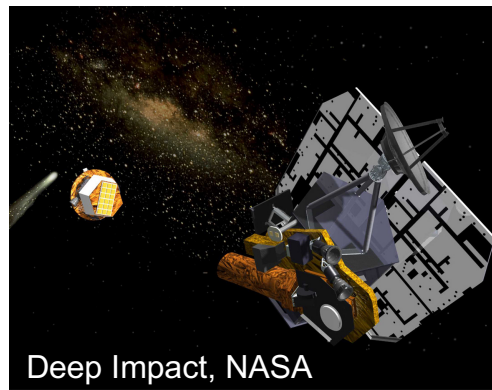
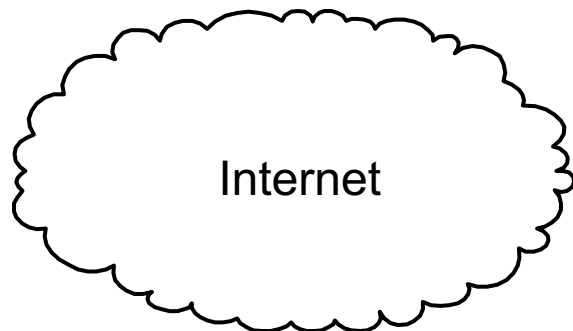
## Bundle Protocol

convergence  
layer adapter  
suited to local  
conditions

TCP

Licklider (LTP)

custom



something  
else

# Basic Bundle structure – blocks.

Primary Bundle Block

|  |       |
|--|-------|
| version  | flags |
| Block length   |       |
| Offsets into Dictionary identifying source, destination, custodians etc. |       |
| Timestamps and lifetime  |       |
| Dictionary information listing Endpoint Identifiers (EIDs)               |       |
| Any fragmentation and length info  |       |



First Payload Block

|                                   |       |        |
|-----------------------------------|-------|--------|
| type                              | flags | length |
| Any references to Dictionary EIDs |       |        |
| payload                           |       |        |

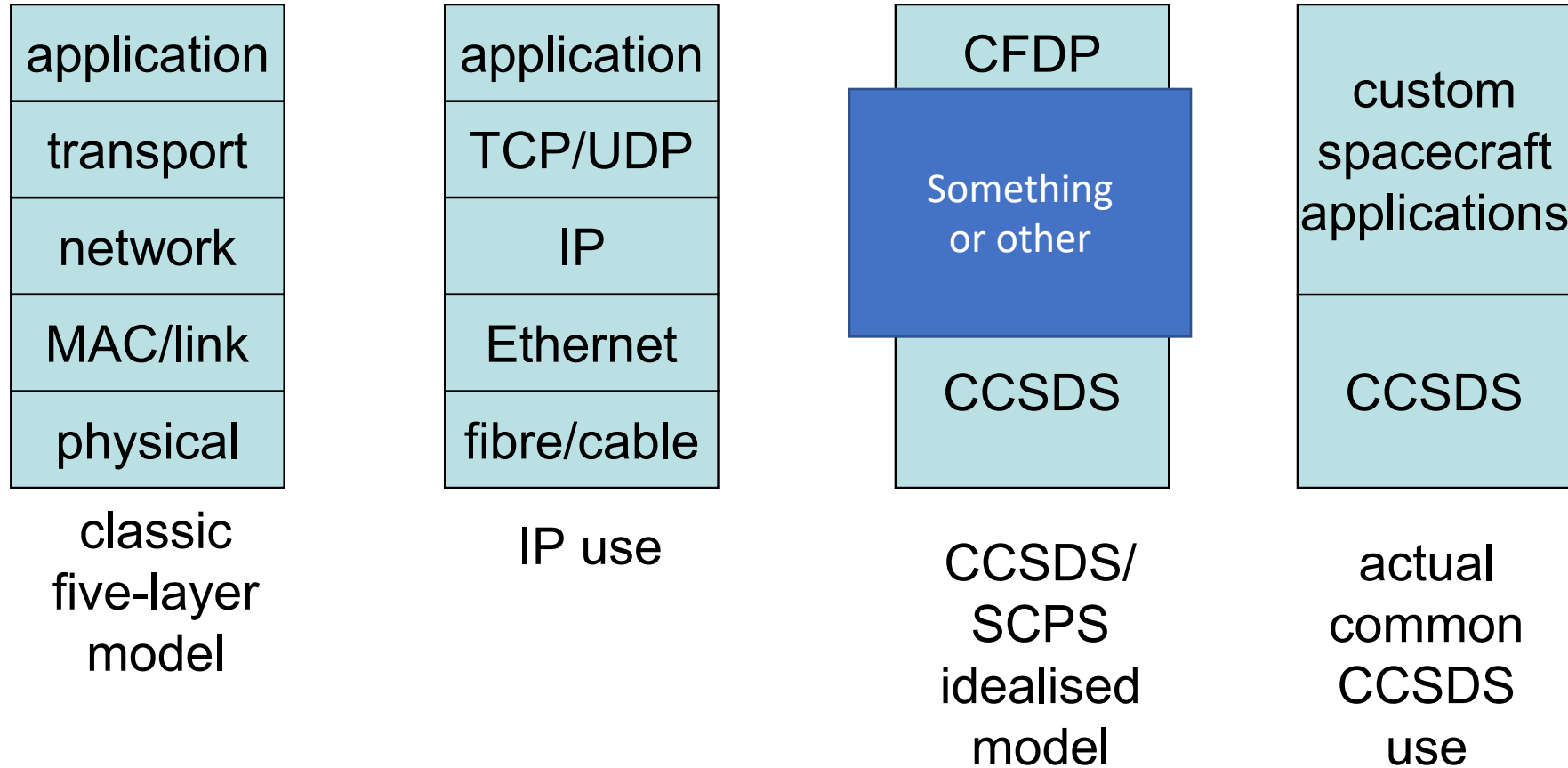


*n*th Payload Block

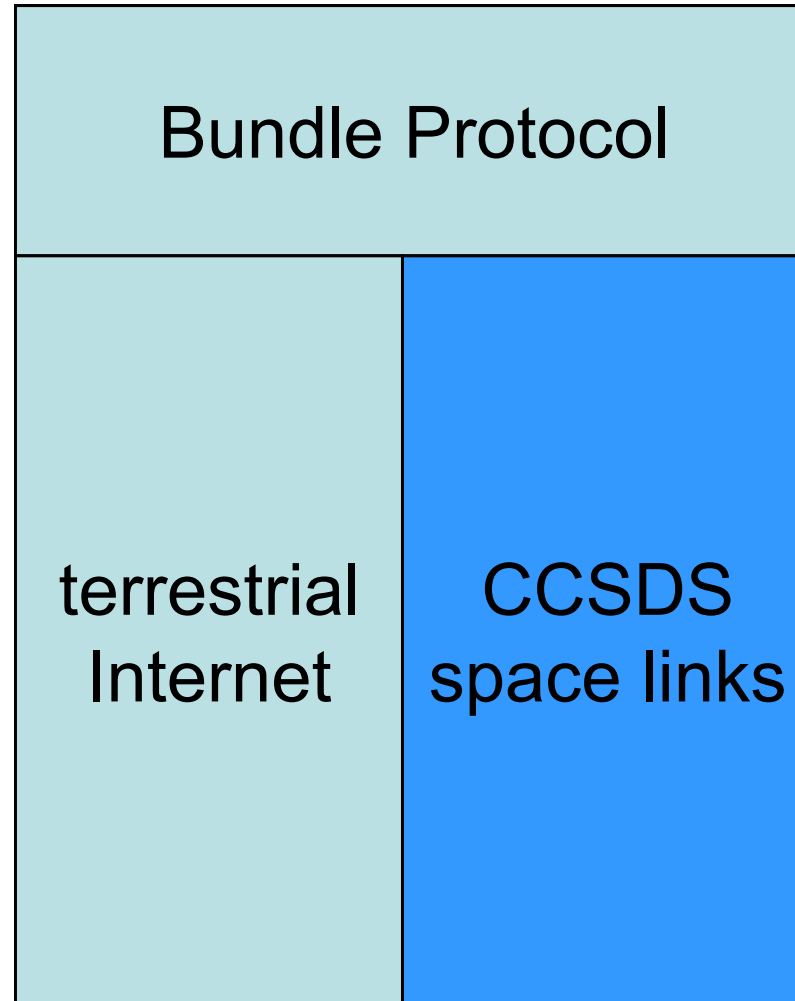
|                                   |       |        |
|-----------------------------------|-------|--------|
| type                              | flags | length |
| Any references to Dictionary EIDs |       |        |
| payload                           |       |        |

Most fields use SDNVs (Self-Delimiting Numeric Values, like ASN.1) and are not fixed-length.  
No checksums. No end-to-end reliability.

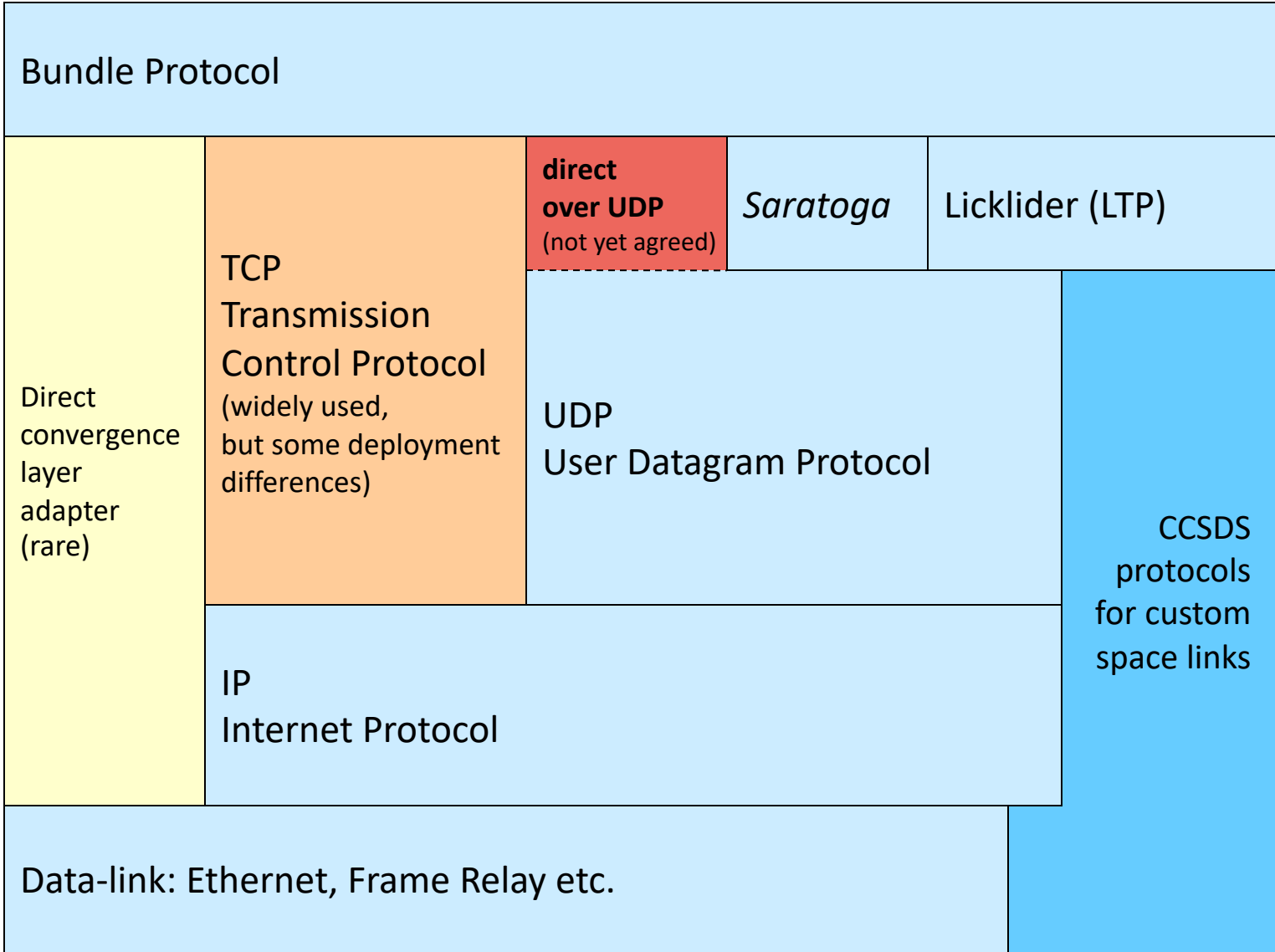
# Existing terrestrial and space stacks



# Bundle Protocol could keep CCSDS and Internet separate and self-contained....



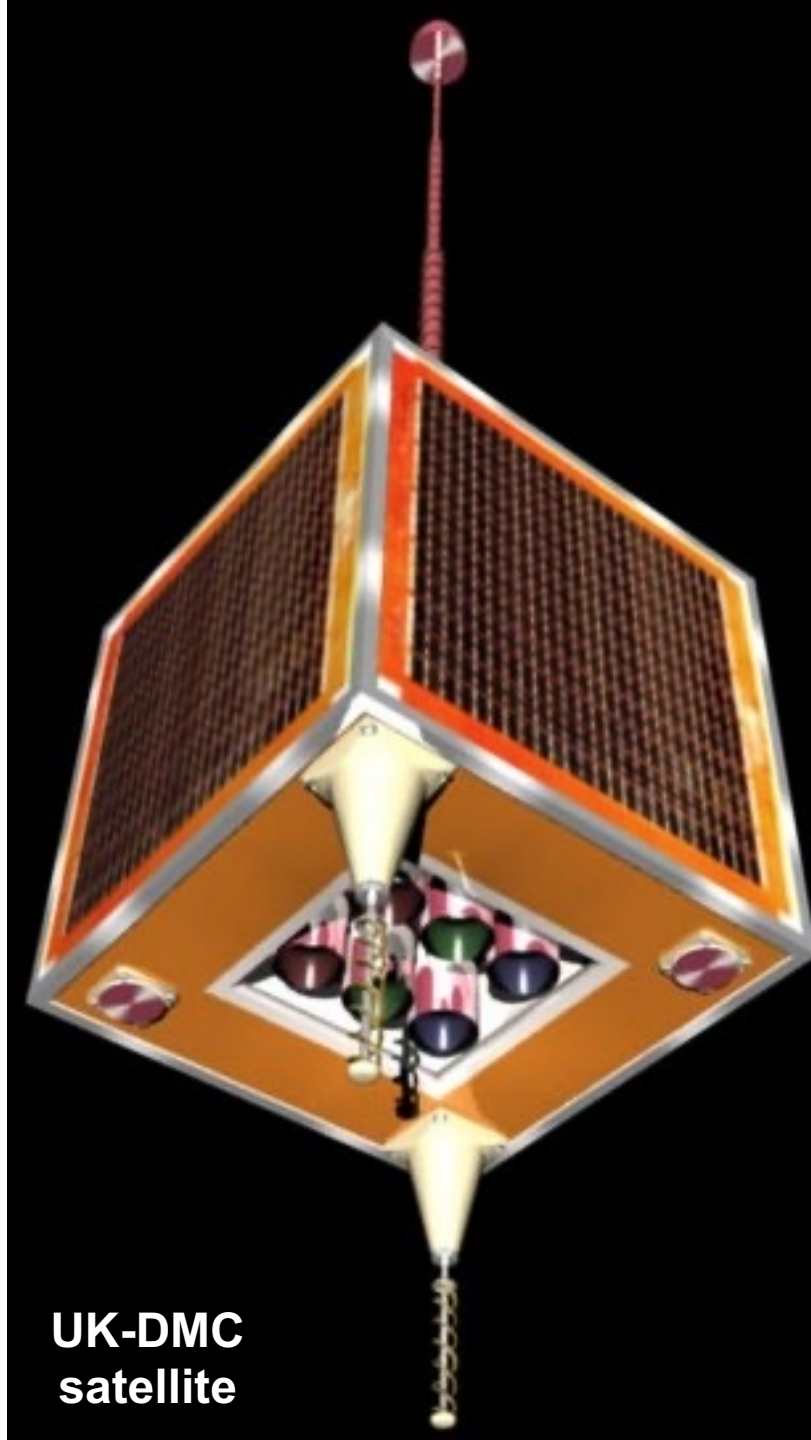
# Existing convergence layers for the Bundle Protocol



Most Bundle Protocol use is over IP. Except for the CCSDS world, of course.

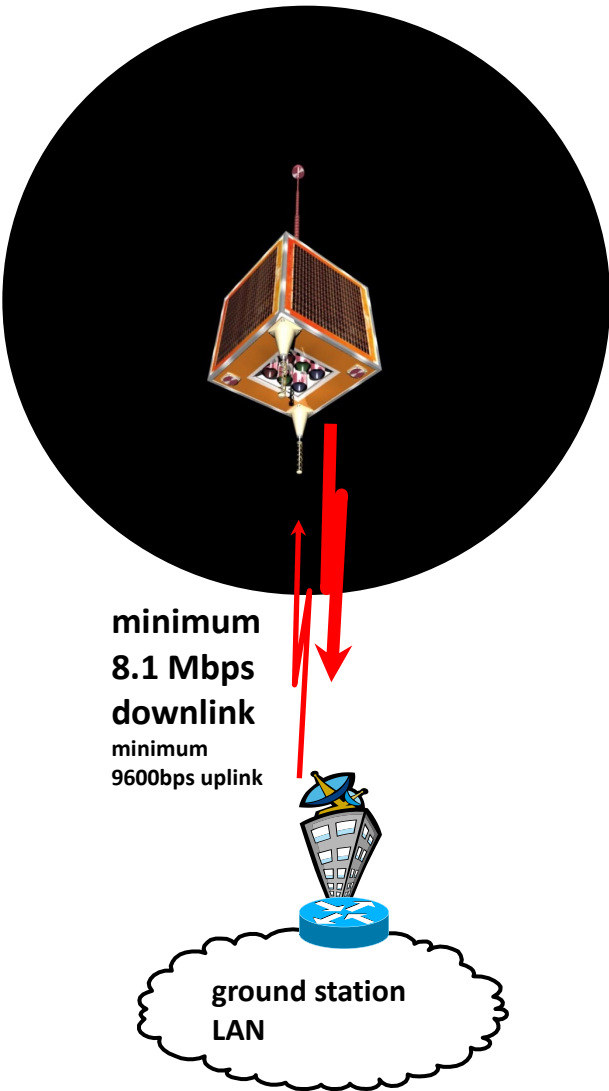
# Short summary of *Saratoga*

- *Saratoga* is a simple and fast file transfer protocol ideal for file transfers over private links or for delay/disruption-tolerant networks.
- Developed and in use by Surrey Satellite Technology Ltd (SSTL) to transfer remote-sensing imagery from IP-based LEO satellites.
- We enhanced the basic *Saratoga* design and took it to the IETF: **draft-wood-tsvwg-saratoga**.
- Multiple implementations (RTEMS, C++...)
- We have tested *Saratoga* with RTEMS-based computers on SSTL's UK-DMC satellite and in our ground-based testbed.
- Public implementations *still* a work in progress.



**UK-DMC  
satellite**

# How is *Saratoga* used in DMC operations?



Each DMC satellite has multiple onboard computers. The Solid State Data Recorders (SSDRs) control cameras and store and download images using *Saratoga* over UDP/IP.

UK-DMC downlink for image files is a minimum of 8.1Mbps.

Newer satellites added 20/40 Mbps X-band downlinks for added hi-res cameras; then faster downlinks (100+ Mbps).

Uplink was only 9600bps for command and control. Uplink speeds increased... 38400 bps! And up!

*Very* asymmetric; 850:1 or worse downlink/uplink ratio.

As much data as possible must be transferred during a pass over a ground station. Passes may be up to fourteen minutes, depending on elevation. At 8Mbps, that's approximately 650MB of useful data (about a CD-ROM-full) that can be transferred in a high pass – if the downlink is filled with back-to-back packets at line rate.

Link utilization and efficiency *really matter*. SSDRs take scheduled turns filling link.

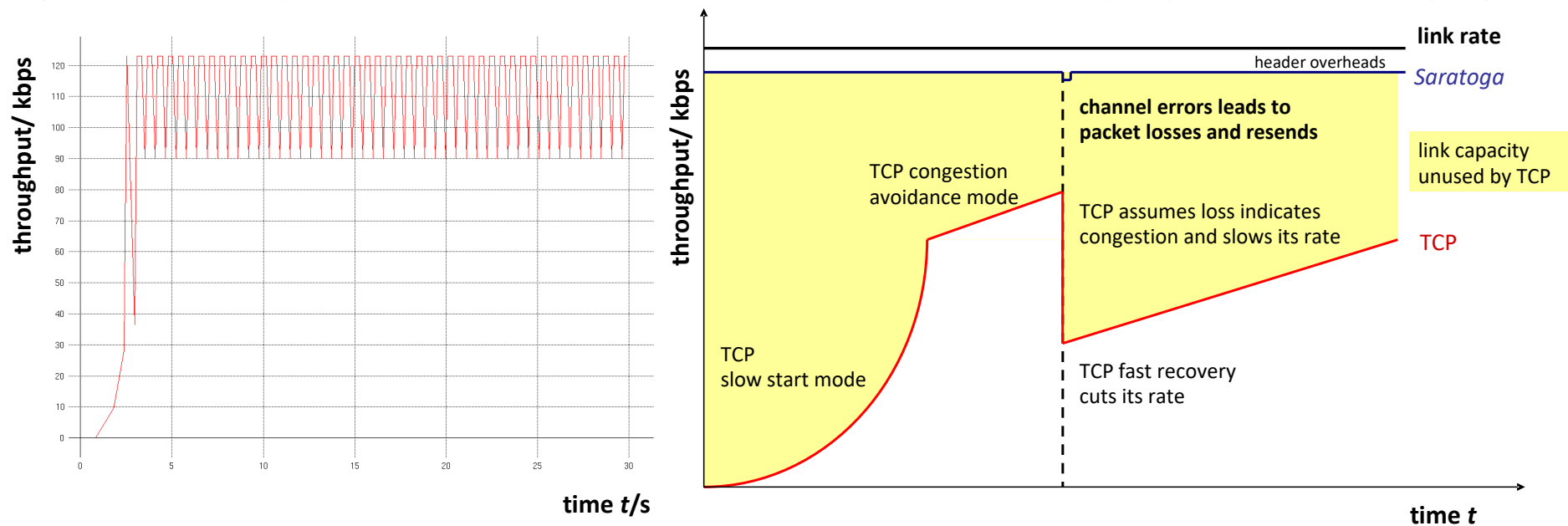
# An approach to DTN networking

- **We believe that the Internet Protocol (IP) is useful for operational use in delay or disruption-tolerant networks.** Being convenient and cheap are compelling reasons to use IP for DTN. IP runs over many links already. Implementing support for custom “DTN bundle” convergence layers directly over all these links simply isn’t scalable or cost-effective. Many IP-based protocols can be reused for DTN.
- The DMC is an example of using IP both on the ground and in space, with the ground station acting as a gateway between different types of network links.
- How IP is used differs between ground and space (link use, shared contention vs dedicated scheduling models – this discourages TCP reuse) but the base IP protocol remains the same. DMC satellites provide a real DTN scenario, with long disruptions between passes over ground stations.

# Saratoga's approach

Run as fast as possible, at maximum possible rate over a private dedicated link. Deliberately **don't** emulate TCP's cautious congestion-control behaviour.

(‘TCP friendly’ behaviour could be added without changing packet design.)



A single TCP flow can't fill a link – reaches capacity, then backs off.

A single *Saratoga* flow can take advantage of all the available capacity.

# Why *Saratoga* instead of TCP?

- For high throughput and link utilization on dedicated links, where a single TCP flow cannot fill the link to capacity.
- For links and link use where TCP's assumptions about loss/congestion/competition simply don't hold.
- Able to cope with high forward/back asymmetry (>850:1).
- Long delay use – eventually TCP will fail to open a connection because its SYN/ACK exchange won't complete. TCP has many unwanted timers.
- Simplicity. TCP is really for a conversation between two hosts; needs a lot of code on top to make it transfer files. A focus on just moving files makes *e.g.* sequence nos. simpler. Having SNACKs means that handling sequence number wraparound when streaming becomes easy.

***USS Saratoga (CV-3) is sunk off Bikini atoll.  
Chris Jackson of SSTL has dived there.***



# Bundle Protocol tests in space

- On Surrey Satellite Technology's UK-DMC satellite, first in January and September 2008. Used Bundle Protocol over *Saratoga*.
  - downloaded real operational sensor data, transferred fragments across Internet from Surrey to NASA Glenn, reassembled image.
- On NASA JPL *EPOXI* (Extrasolar Planet Observation and *Deep Impact* eXtended Investigation) comet probe, October 2008. Used Bundle Protocol over LTP over CFDP over lots of stuff. (DINET – Deep Impact DTN Experiment)
  - Uploaded pictures to probe, got them back again. Implemented ground network simulating other probes.

# Example pictures sent to *EPOXI* and back

- Uplink at 250 bytes/sec, downlink at either 110 or 20,000 bytes/sec.
- One-way propagation delay of 81s, down to 49s four weeks later.
- About 300 images relayed through Deep Impact and back as a 'DTN router'



JCR Licklider, DARPA

Famous *Galactic network* memo

# Sensor data we downloaded using Bundle Protocol

150MB image transferred from UK-DMC satellite using Bundle Protocol over *Saratoga* with proactive fragmentation, 25 August 2008.

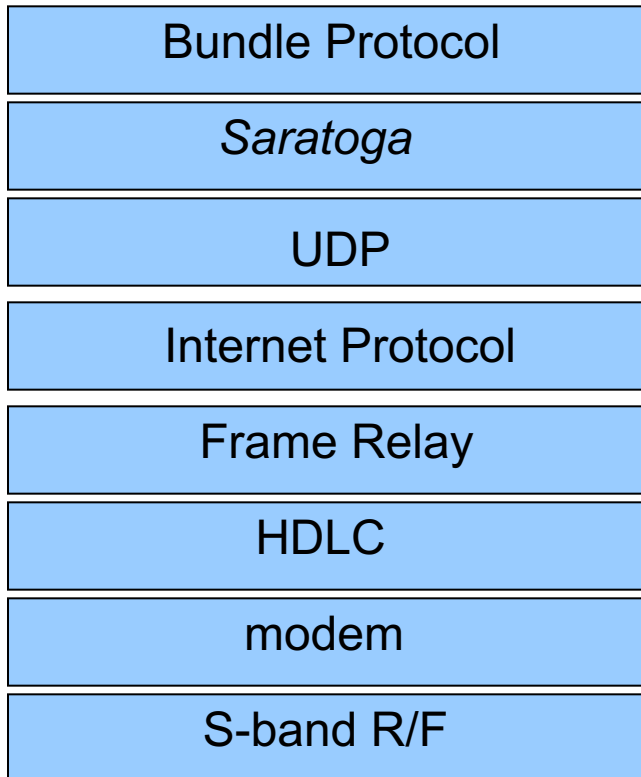
*TIME Magazine* best inventions of the year #9 **Orbital Internet**, 10 November 2008 issue – before *EPOXI* tests announced.

[www.dmcii.com](http://www.dmcii.com)



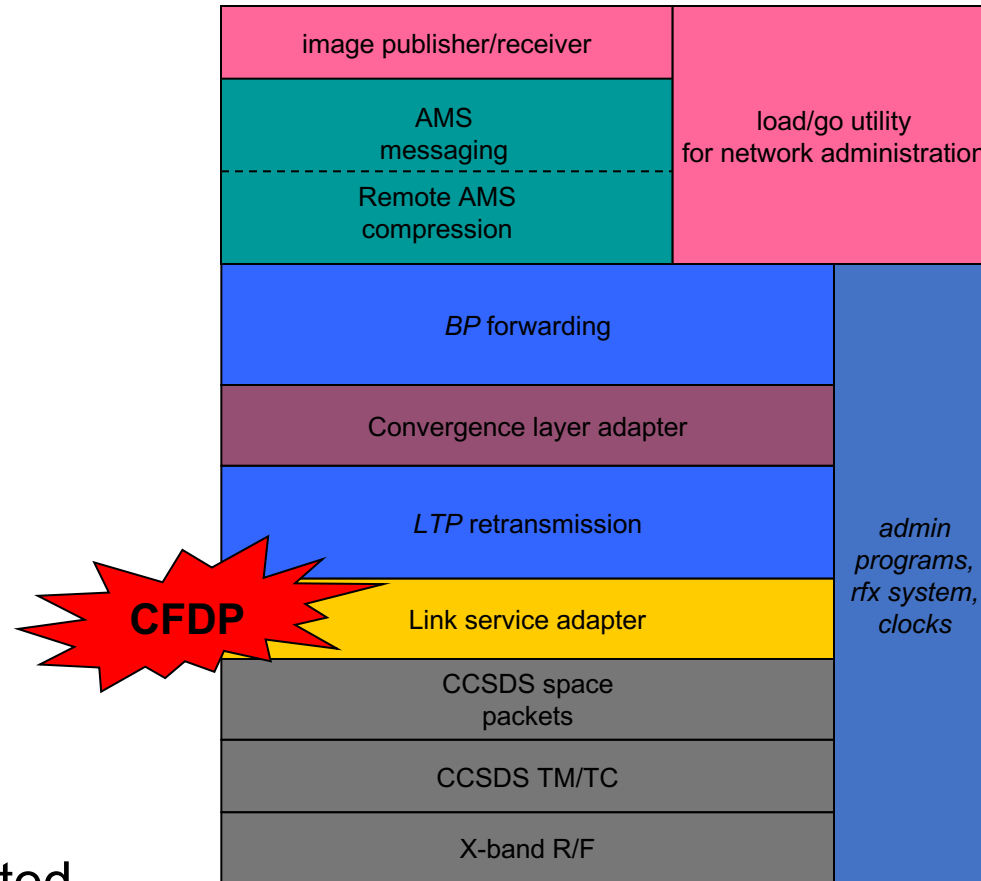
# Networking stacks used in these experiments

UK-DMC tests, Jan/Sep 2008  
after Hogue. Max possible bundle size: 4GB



Bundle security not implemented  
onboard either spacecraft.

Deep Impact, Oct 2008  
after Burleigh. Max possible bundle: 64K



Scott Burleigh, IETF 73 DTNRG meet, 20 Nov 2008

# Some problems with bundling

- **Reliability.** No error detection, and reusing security to give reliability is not ideal. (End-to-end principle.)
- **Timing.** Every bundle agent is expected to know current UTC time. This has limits in space (clocks drift with temperature). Synchronization is a problem; bundles can be dropped as expired.
- **Convergence layer adapters.** Pretty much all use and deployment is over IP – *except* for CCSDS.
- naming schemes/routing/QoS/management.
- No content identification *a la* MIME and HTTP...
- How large is a bundle? Is it the application... or the network?

# CCSDS vs IP/FR/HDLC for space – brief history in a slide

time

## CCSDS stack world (NASA JPL) '70s-

- Custom protocols over CCSDS links.
- Standards by fiat – adopted by very small community, but are ISO standards as CCSDS is ISO subgroup.
- No clear layering, for optimisation of link budgets via high integration. Not modular, must be re-engineered when lower layers change waveform: costly.
- Claimed use on hundreds of (incompatible) missions, over decades.
- Legacy streaming, rather than packet/files. Missions do not use files.
- CCSDS links do not carry IP well.
- Expensive to (re)develop whenever link coding changes the waveform.

## IP stack world (NASA Goddard/Glenn) '90s-

- UDP/IP over frame relay/HDLC.
- IETF and other commercial standards are widely used and implemented.
- *Made CLEO router in orbit and first DTN 'bundle' tests in space possible.*
- Fully layered and modular, for plug and play and simple integration. Just change modem to support a new physical coding.
- Used on over twenty missions since 1999, *e.g.* DMC satellites.
- Full support of packet/file transmission and networking concepts.
- Carries IP very cleanly and well.
- Cheap to develop; tools and knowledge widely available.

**CFDP – CCSDS File Delivery Protocol.** Like FTP with many added features. Intended to be used over both IP and over CCSDS – but is not in use over IP.

**DTN Delay-Tolerant Networking bundles.** Replaces CFDP. Intended to run over CCSDS and over IP via adaptation layers. Developed cheaply over IP. But CCSDS wants DTN over legacy CCSDS links and waveforms to migrate their userbase.


# Some thoughts

- Standards for space are a good thing – but does space need its own standards? CCSDS says ‘yes,’ but at the same time promotes the Bundle Protocol for many other environments.
- Why didn’t CCSDS let ISO-standard HDLC run over ISO-standard CCSDS protocols?
- Is the Bundle Protocol a failure for not meeting the needs of its various problem spaces? Or is expecting too much of it simply unreasonable?

# Interplanetary Internet vs intersatellite links

- Idea of intersatellite links has been around for years – but satellites are focused on their particular mission, don't want to waste time/money/launch mass on something unless it's clearly justified. (Constellations change this.)
- Similarly, space probes are very mission-focused. Considering supporting something not in the immediate mission, with extra development cost and unclear benefits? To someone else, not to you? (*Mars Telecom Orbiter* was cancelled. Little relaying on Mars, or with *Cassini-Huygens* at Titan.)
- The Interplanetary Internet, intended to run over a network that doesn't yet exist, might be a hard sell.

# New possibilities with *Saratoga*

- SSTL remote-sensing images grew to cross 4GiB file size, needing >32-bit pointers.
- How to design a *scalable* file transfer protocol able to handle any size file, without requiring separate incompatible implementations for big files?
- Tried to solve this problem with 16/32/64/128-bit pointers and advertising capabilities – *file descriptors*.  
 128-bit not needed - yet!
- 64-bit for files <16 exabytes. 128-bit: <256 exa-exabytes!
- Could be useful for Very Large Data Transfers.

## **For more information**

You could google **UK-DMC bundle**

papers, presentations, videos, specifications in large repository:

<http://lloydwood.users.sf.net/>

**Questions?**

**thankyou!**