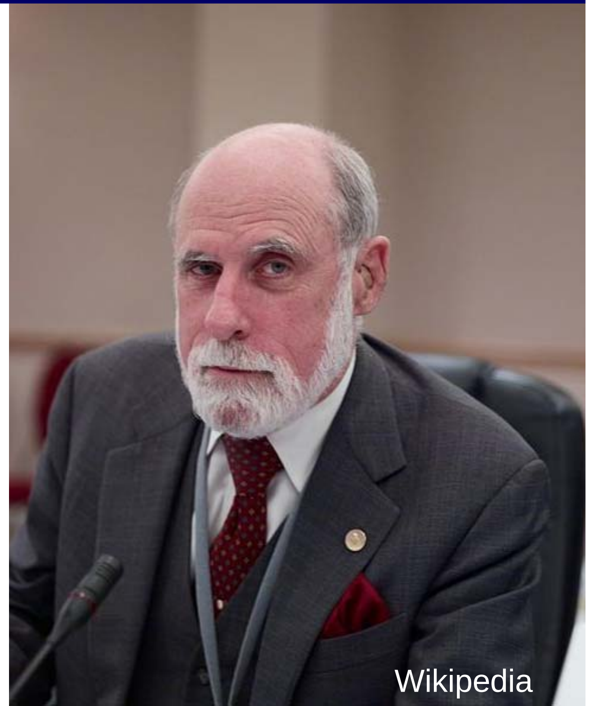
Interplanetary Internet

bringing networking into space onboard UoSAT-12 and UK-DMC

Lloyd Wood
AMSAT-UK international space colloquium
Guildford, Saturday, 30 July 2011.

The Interplanetary Internet?

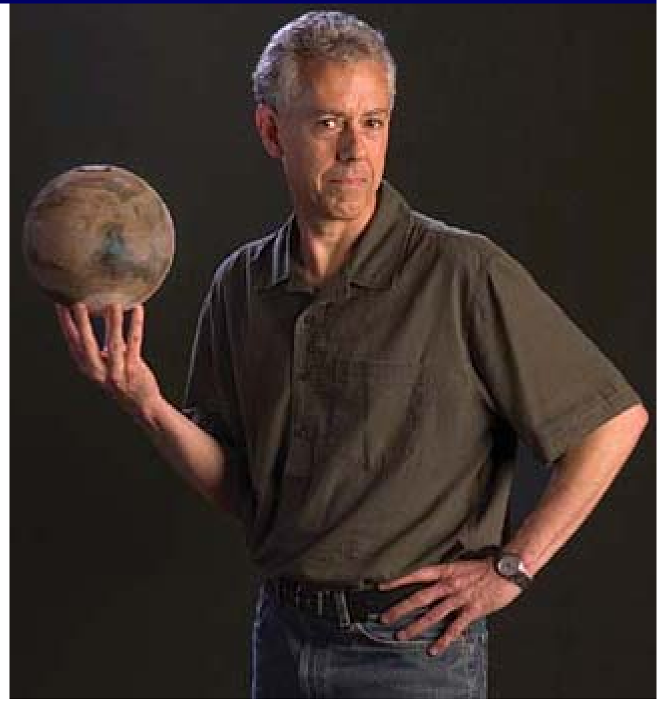
- Vint Cerf announces start of IPN thirteen years ago, in 1998.
- Collaborates with Adrian Hooke of **NASA Jet Propulsion Lab (JPL)** – who leads CCSDS (Consultative Committee for Space Data Systems), an ISO subgroup that sets *standards for space*.
- Space probes predate computing; tape recorder bitstream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


Wikipedia


Associated Press

Scott Burleigh does design engineering for NASA JPL

- Careful consideration of legacy CCSDS base and slow migration.
- Gave us CFDP, Licklider LTP, and Bundle Protocol for IPN.
- CCSDS File Delivery Protocol (CFDP) a bit like Bundle Protocol – layers over everything: TCP, UDP CCSDS, you name it. Complex.
- CFDP (lite) in use by *Messenger* Mercury probe and *Deep Impact* comet mission. Licklider LTP a 'stripped down' CFDP in some ways.



IEEE Spectrum, Aug 2005.

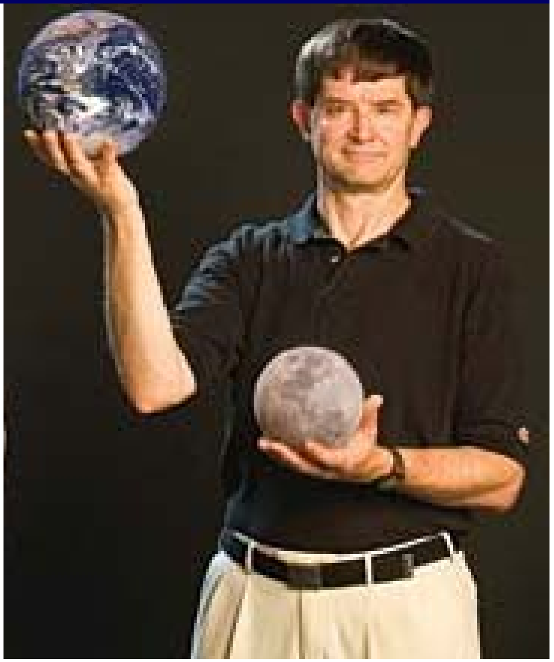
at NASA JPL

CFDP
LTP
Bundle Protocol

CCSDS

Keith Hogie's alternative approach to space networking

- 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. Showed that this worked with Surrey and on final *Columbia* mission.
- HDLC can also be carried easily over CCSDS, as CCSDS supports 'tape recorder bitstream' – easier than CCSDS ways to carry IPv4 (and other ways to carry IPv6). CCSDS is treated as the channel.



IEEE Spectrum, Aug 2005.

Contracts to NASA Goddard.

Effectively designed SSTL approach to IP networking with UoSAT-12.

HDLC/FR/IP

SSTL tries alternative to good old AX.25…

- UoSAT-12 launched 1999. AX.25 for TT&C.
- Prototyped a lot of new technologies – S-band links, cameras, Ethernet, stabilisation… many used in the later Disaster Monitoring Constellation.
- …including an IP stack developed with Hogie at Goddard, fitted over the existing HDLC for AX.25.

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 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. (AlSAT-1 launched in Nov 2002, UK-DMC *et al*. Sep 2003, Beijing-1 Oct 2005…). First just payloads, then platform. Cisco Systems puts CLEO Internet 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.

Disaster Monitoring Constellation (DMC)

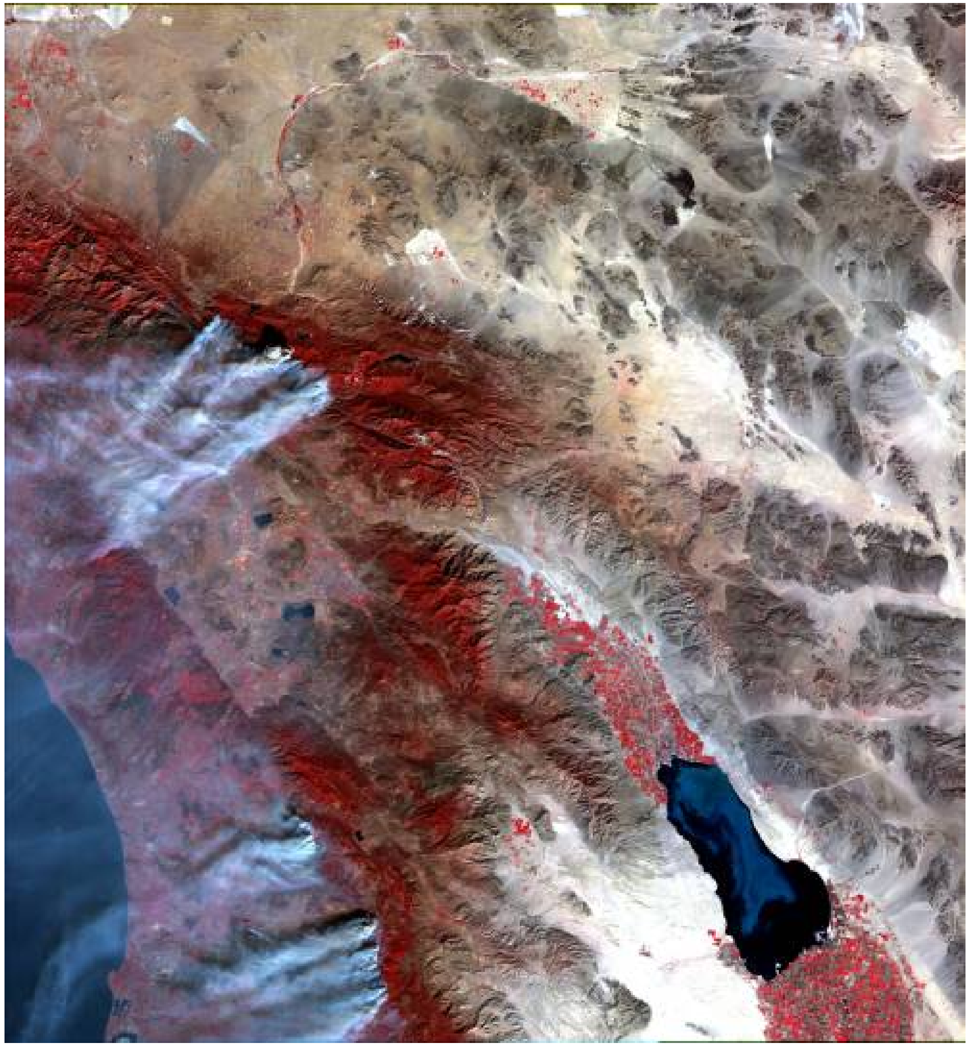
Surrey Satellite Technology Ltd (SSTL) build and help operate an international constellation of small sensor satellites.

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. Also commercial.

Each government finances a ground station in its country and a satellite. Ground stations networked together. Further satellites ready for launch.

www.dmcii.com



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

DMC in use: after Hurricane Katrina, 2005

www.dmcii.com

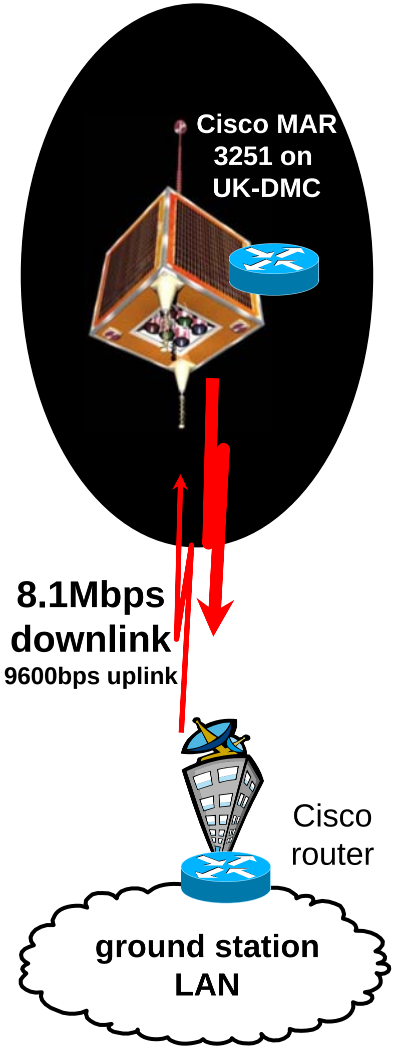
In this false-color image, dry land is red. Flooded and damaged land is shown as brown.

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.

IP networking environment for the DMC



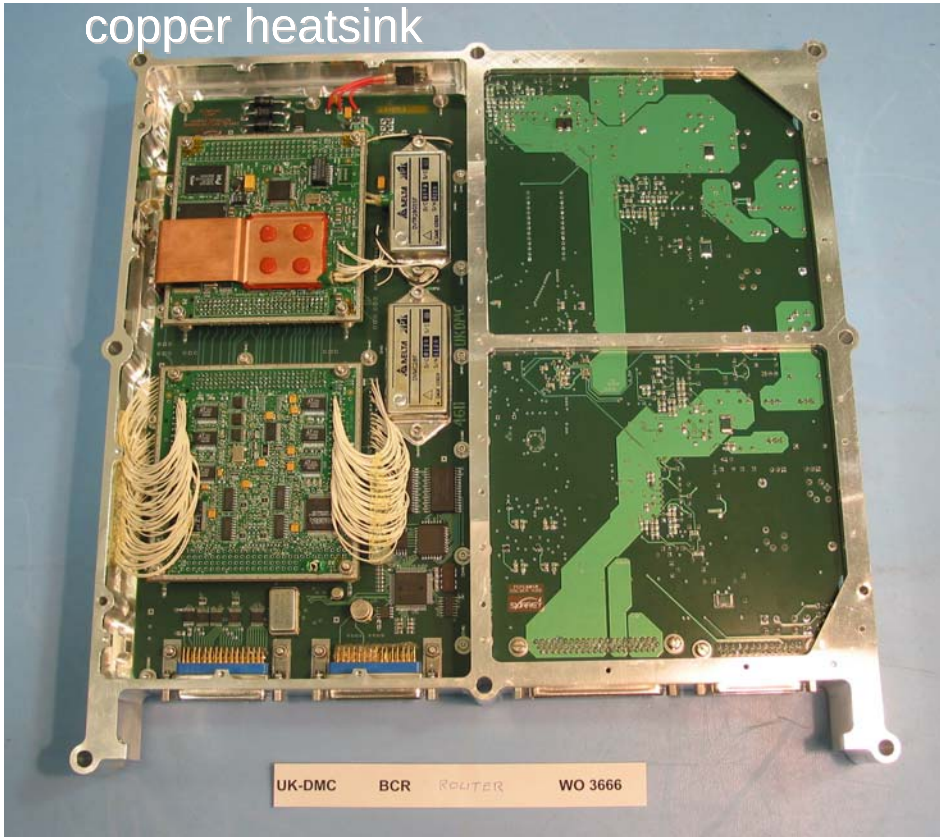
Satellite: each DMC satellite has multiple onboard computers. For housekeeping (the On Board Computer, OBC), for image capture and packetised transmission (the Solid State Data Recorders, SSDRs), for redundancy and survival. Interconnected by IP over 8.1Mbps serial links for data and slower CANbus for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

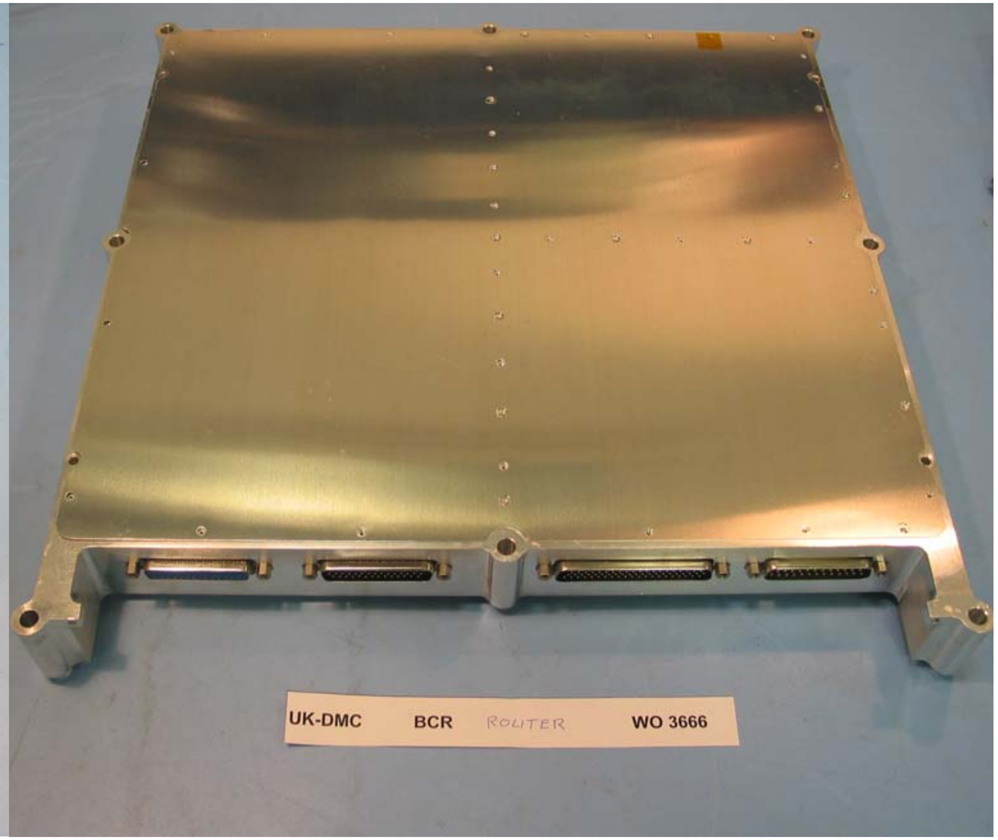
CLEO: Cisco router was able to fit into UK-DMC satellite's onboard network by connecting to OBC and SSDRs using common serial interfaces.

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.*

CLEO Internet router in UK-DMC payload tray

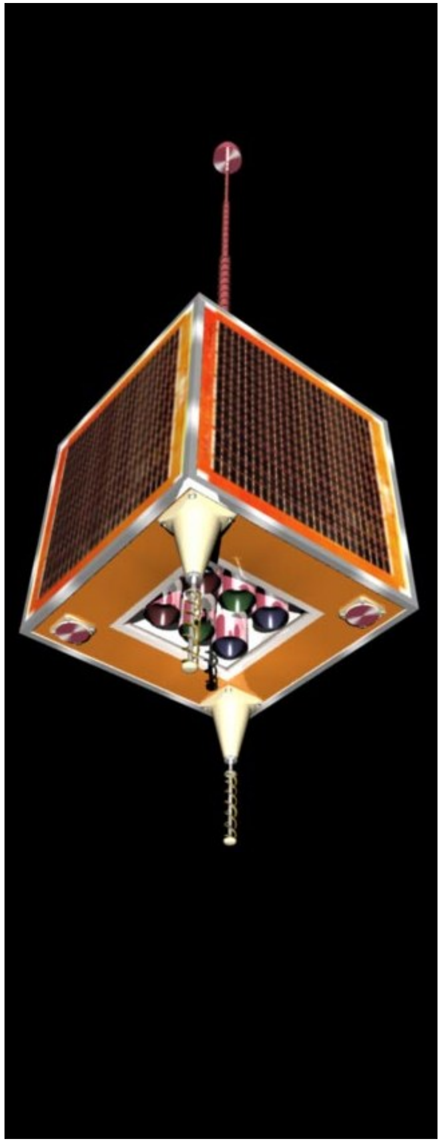
CLEO mobile router and serial card talk to other computers onboard via simple serial links. Possible because of Hogie's serial/HDLC/FR/IP approach allowing integration.





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 still works after years in space.
- Router launched on geostationary satellite (Cisco IRIS on Intelsat-14, November 2009).



Meanwhile, in the Interplanetary Internet…

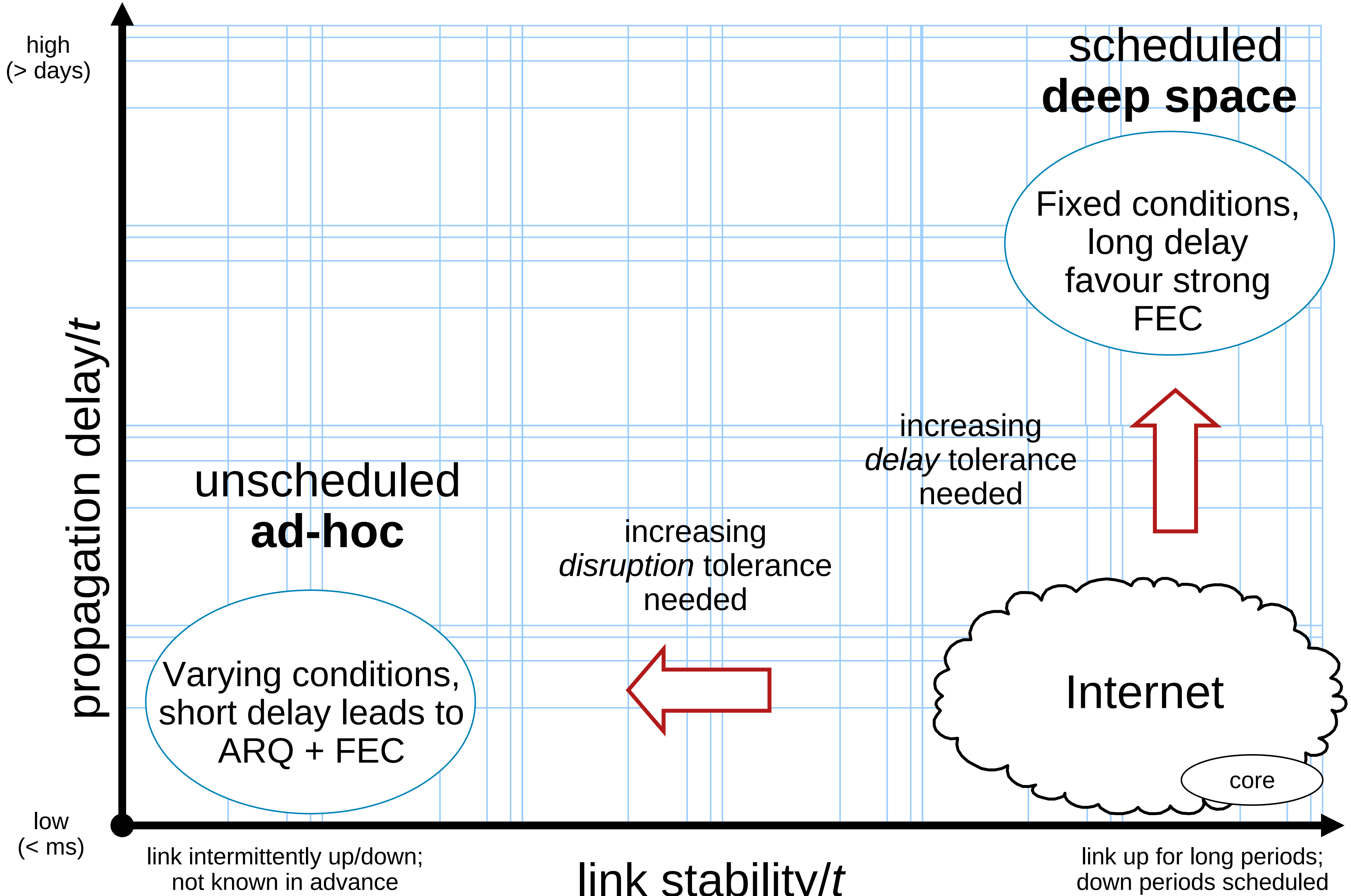
- Internet Society Special Interest Group (IPNSIG).
- Then a short-lived IRTF 'Interplanetary Internet' group (IPNRG) and some internet-drafts, 2001.
- Problem scope widens to 'Delay Tolerant Networking' (Kevin Fall in SIGCOMM).

- 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.)

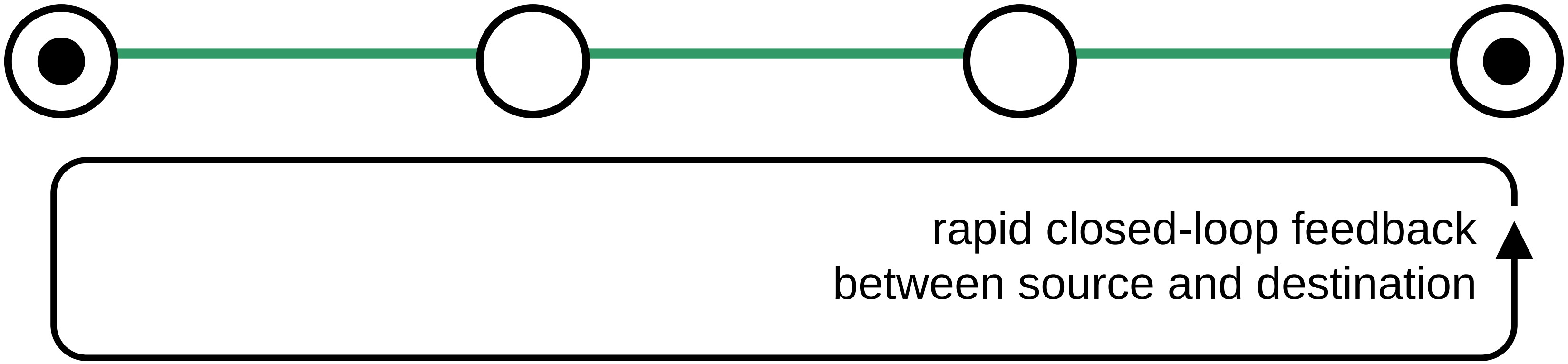
Problem scope was consistently widened

- 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 will it still solve the original problem?

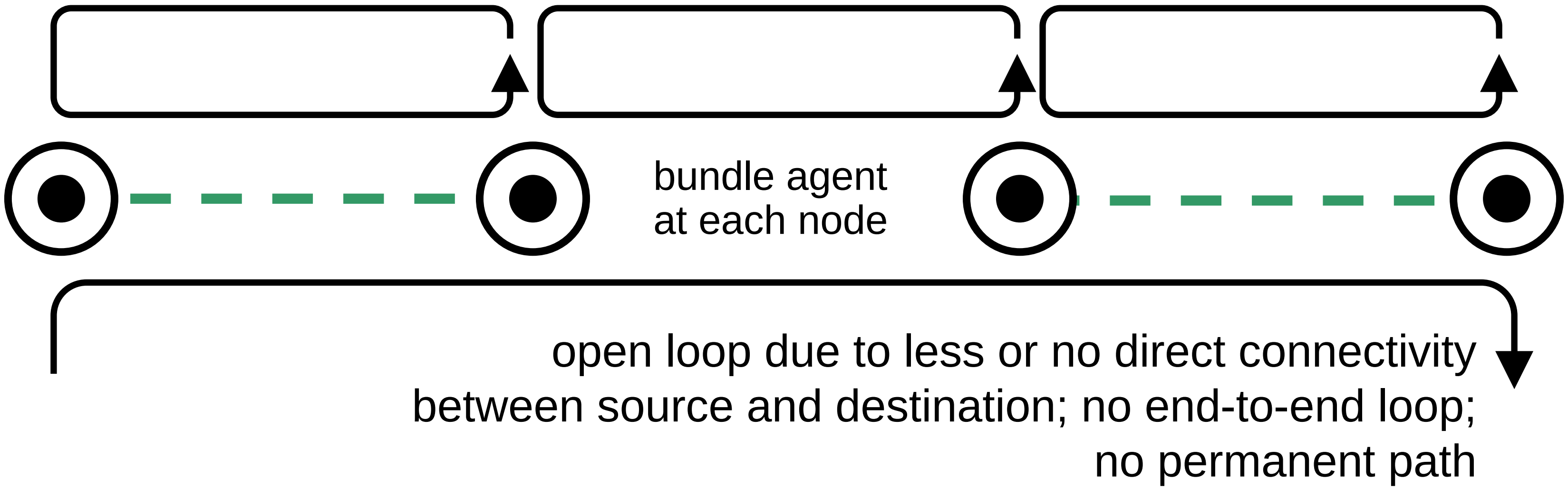
Two different problem spaces



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



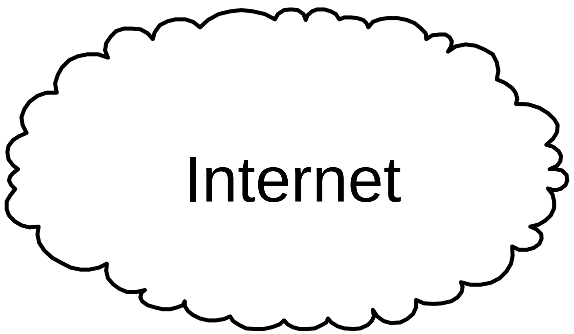
Bundle Protocol developed for DTN

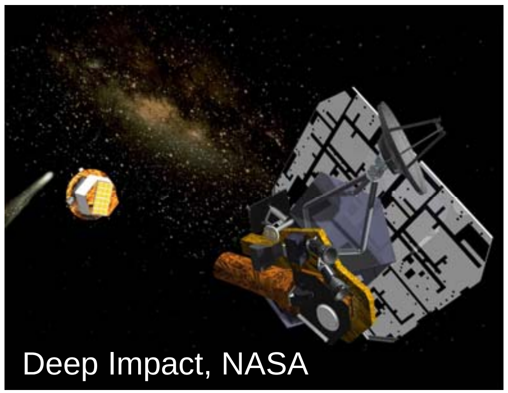
- This layers over different *internets*, just as the Internet Protocol layered over different *networks*.
- Uses 'convergence layer adapters' which are responsible for reliable transmission and delivery over each network.

Bundle Protocol

convergence layer adapter suited to local conditions

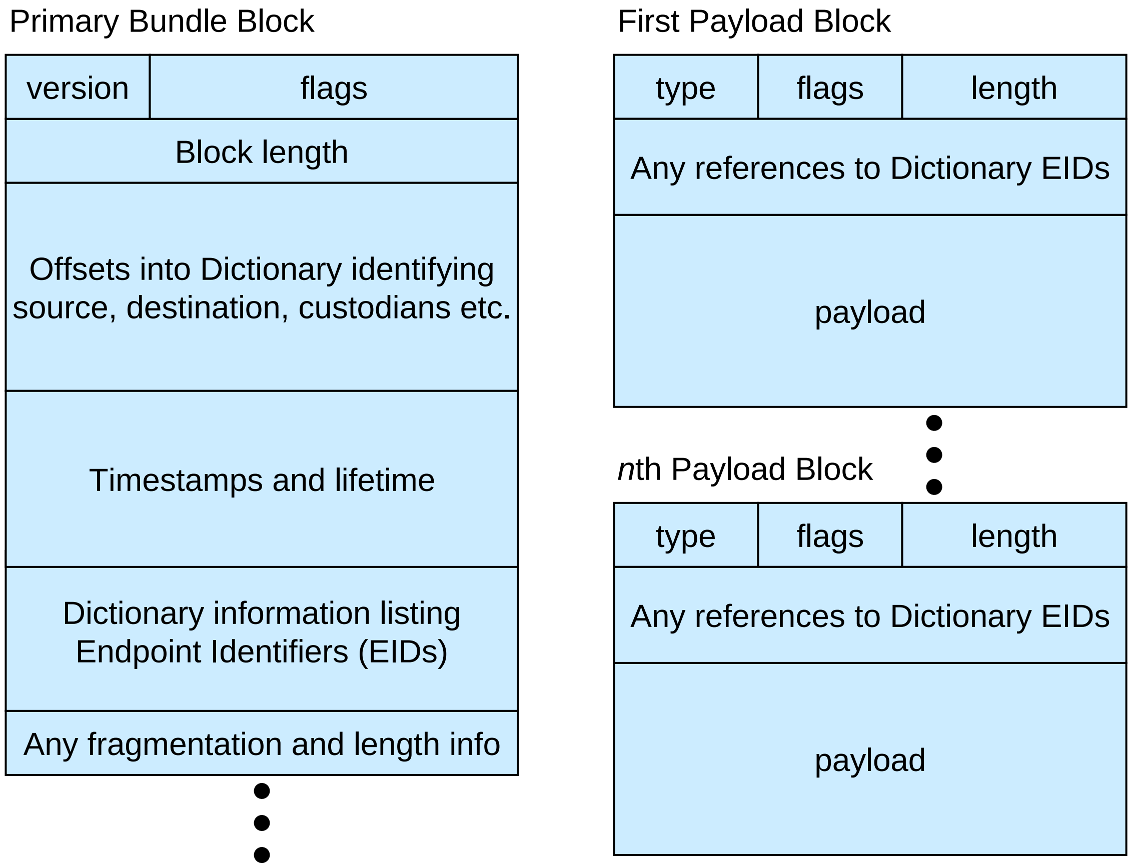
TCP | Licklider (LTP) | custom




Deep Impact, NASA

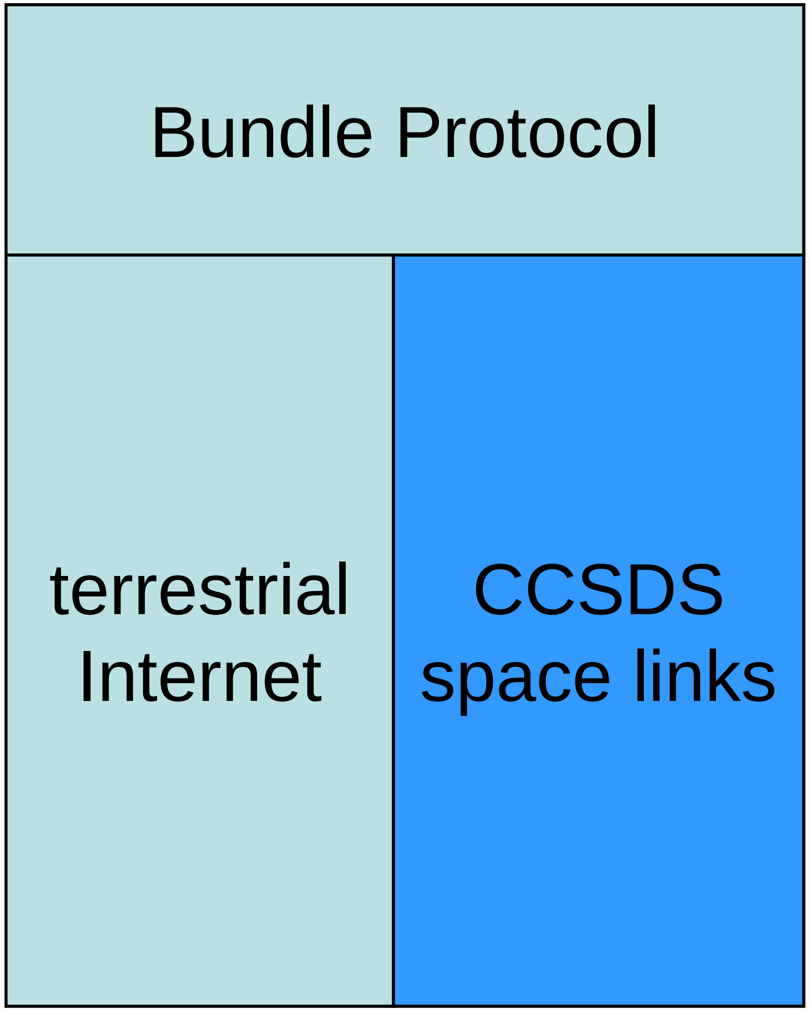
something else

Basic Bundle structure – blocks.

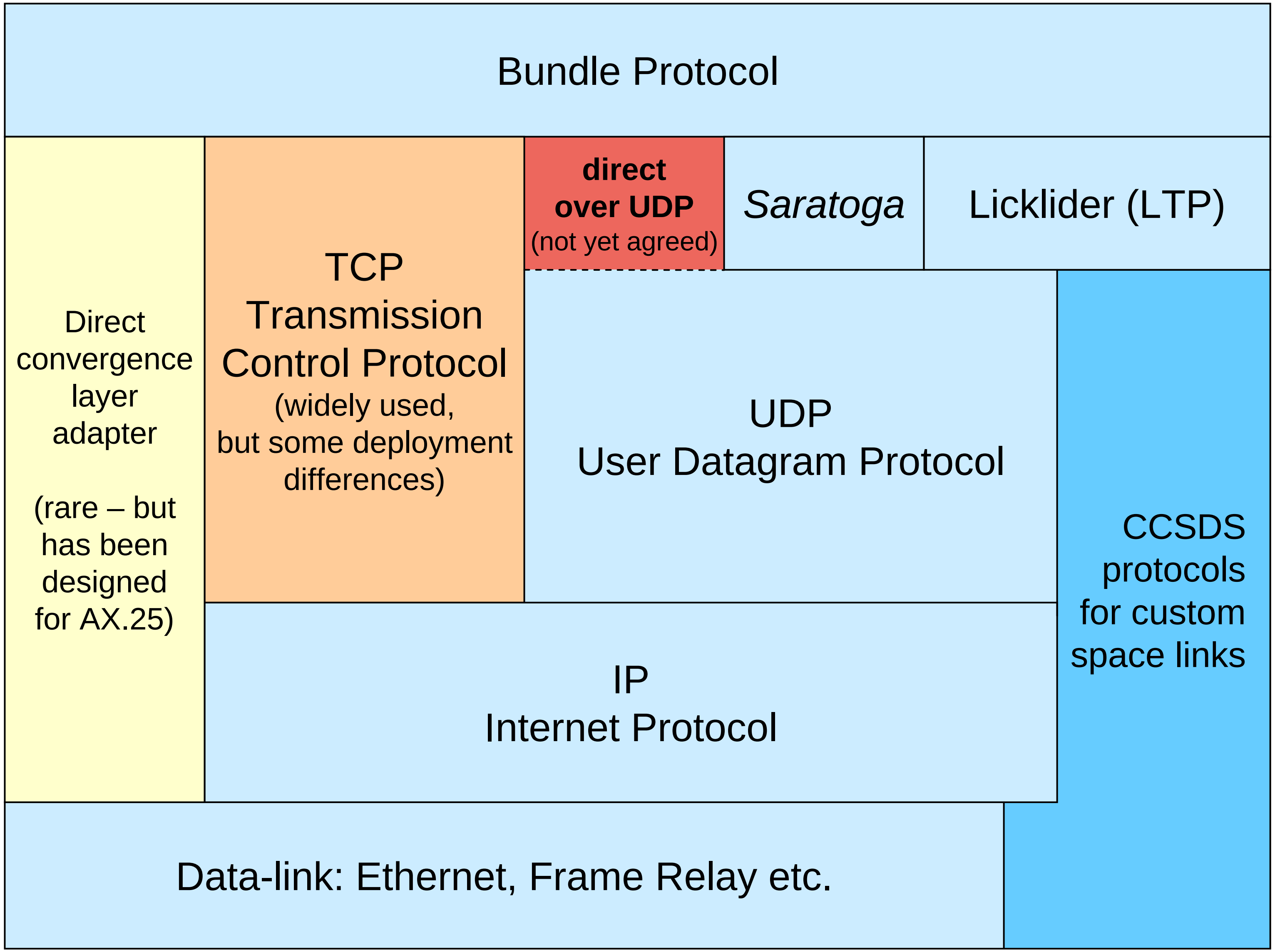


Most fields use SDNVs (Self-Delimiting Numeric Values, like ASN.1) and are not fixed-length.
No checksums. No end-to-end reliability.

Bundle Protocol could keep deep space and Internet separate and self-contained….



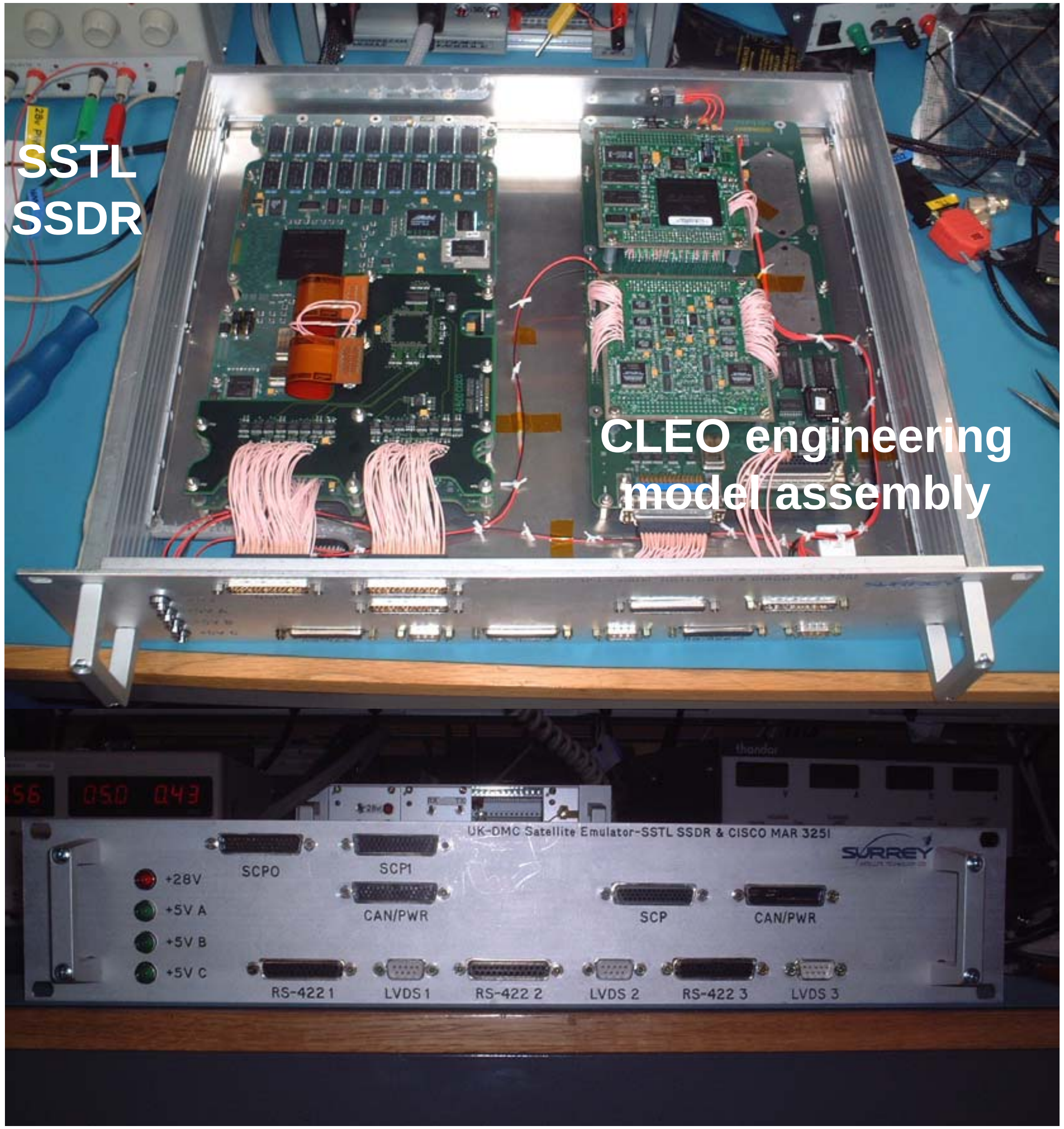
Existing convergence layers for the Bundle Protocol



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

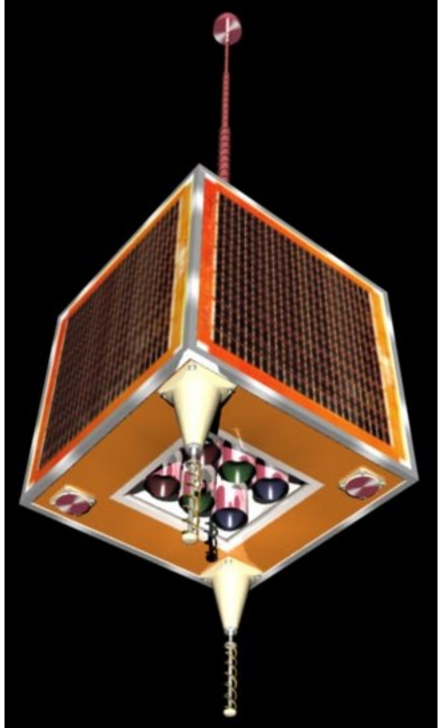
CLEO ground testbed enabled new development

- Ground-based testbed loaned to NASA Glenn was key to success of testing CLEO router to deadline.
- IPv4/IPSec/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 on *Saratoga.*



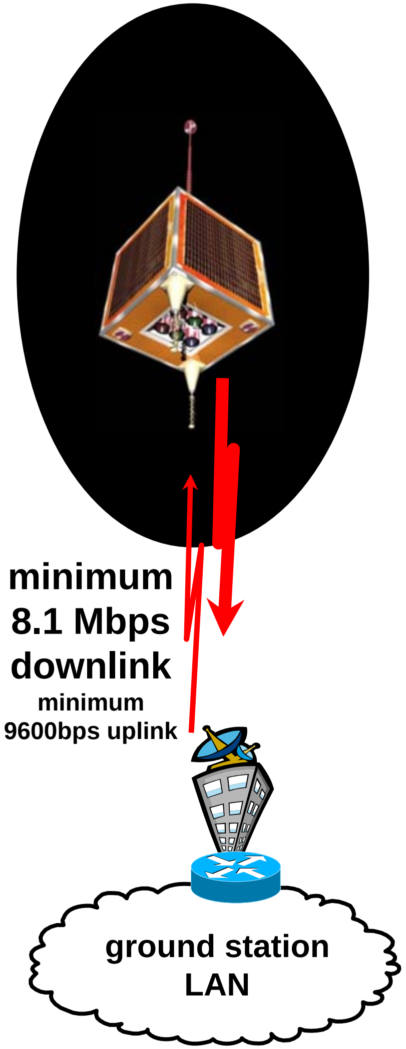
Short summary of *Saratoga*

- *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 redesigned *Saratoga* and took it to the IETF: **draft-wood-tsvwg-saratoga-09.txt**.
- We already have multiple implementations (in Perl, C, C++, on Linux and RTEMS).
- We have tested *Saratoga* with RTEMS-based computers on SSTL's UK-DMC satellite and in our ground-based testbed.



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.

DMC downlink for image files is a minimum of 8.1Mbps. Newer satellites also have 20/40 Mbps X-band downlinks for added hi-res cameras; faster downlinks (100+ Mbps) are planned for future missions. Uplink is only 9600bps for command and control. Uplink speeds are also likely to increase… but only to 38400 bps.
Very asymmetric; 850:1 or worse downlink/uplink ratio.

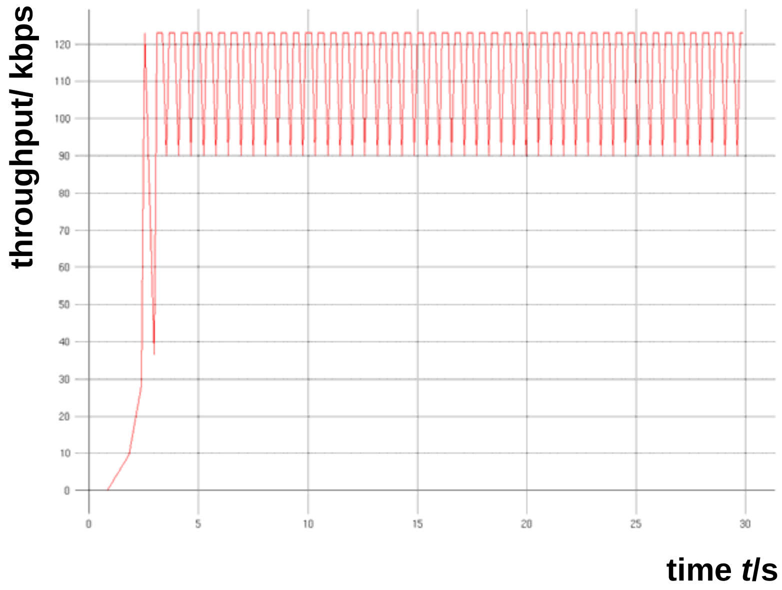
As much data as possible must be transferred during a pass over a ground station. Passes may be up to fourteen minutes, depending on elevation. At 8Mbps, that's approximately 650MB of useful data (about a CD-ROM-full) that can be transferred in a high pass – if the downlink is filled with back-to-back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

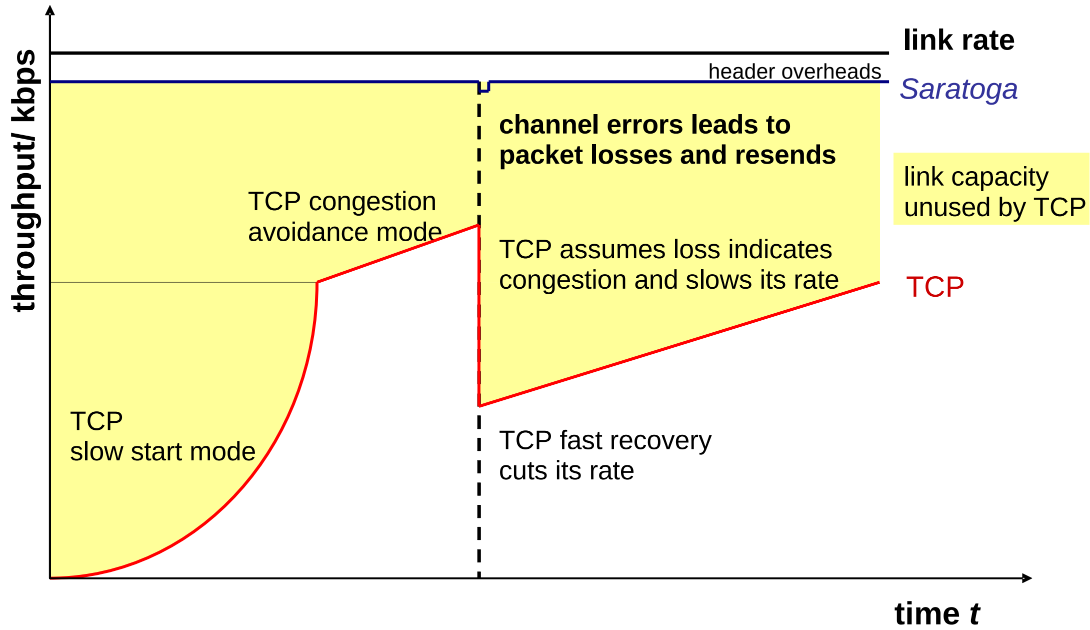
An approach to DTN (and space) networking

- **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 high-speed delivery

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 can be added without changing packets.)





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.

Why is it called *Saratoga*?

Photo # 19-N-84312 USS Saratoga underway in Puget Sound, 15 May 1945

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

Saratoga can provide reliable transfers.

- *Saratoga* always uses the UDP checksum to cover header and payload. This is consistent but not that strong (one's-complement), and not end-to-end.
- An end-to-end MD5 checksum over the entire file being transferred increases confidence that a reliable copy has been made, or that fragments have been reassembled correctly. Strong link-layer checksums are optional.
- The IRTF DTN research group's Bundle Protocol and its convergence layers lack any reliability checks, ignoring the *end-to-end principle*. We have proposed ways of adding reliability back to the DTNRG bundle protocol.

Bundle Protocol tests in space

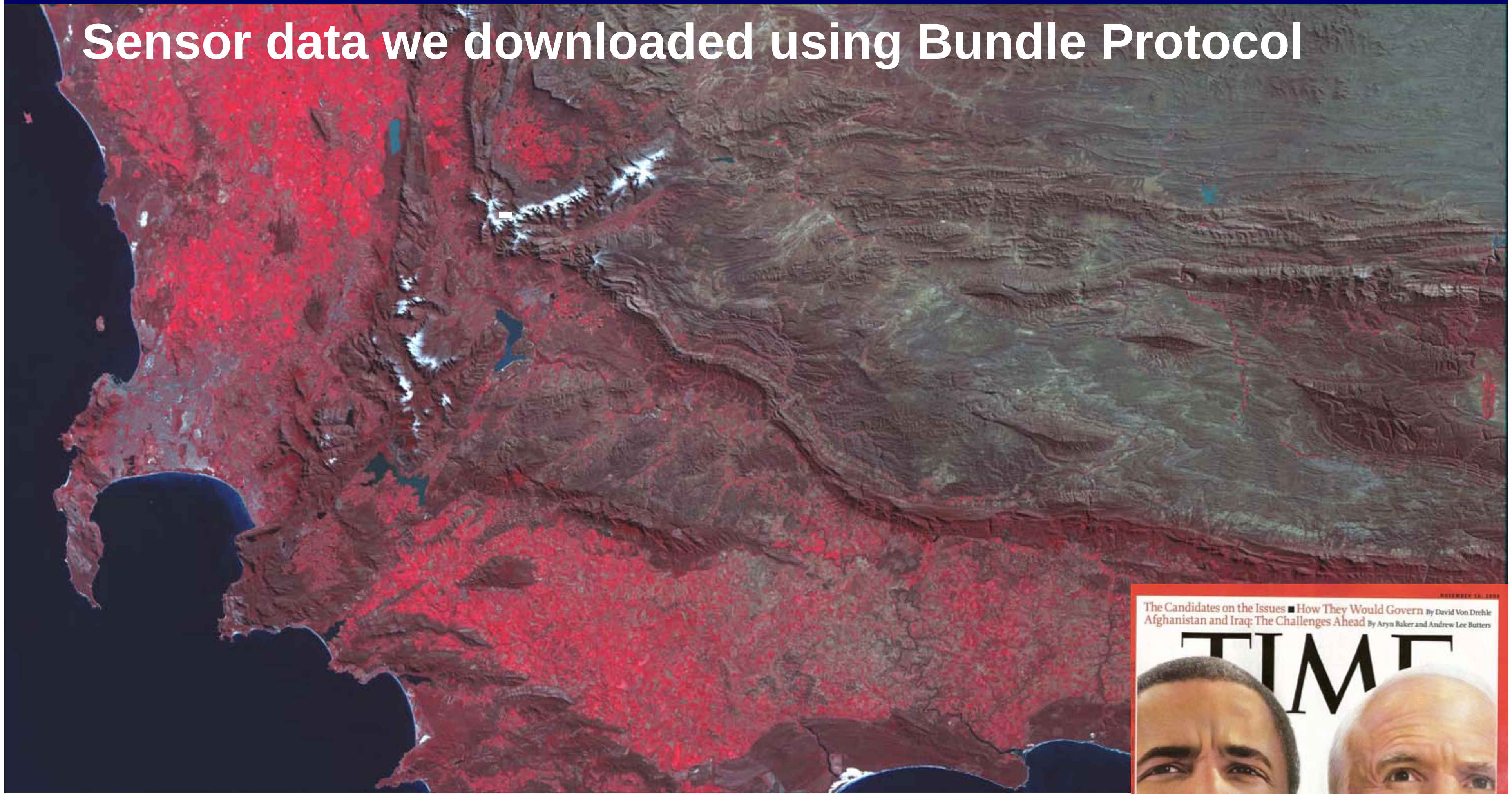
- On Surrey Satellite Technology's UK-DMC satellite, first in January and September 2008. Used Bundle Protocol over *Saratoga*.

  downloaded real operational sensor data, transferred fragments across Internet from Surrey to NASA Glenn.

- 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.

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.

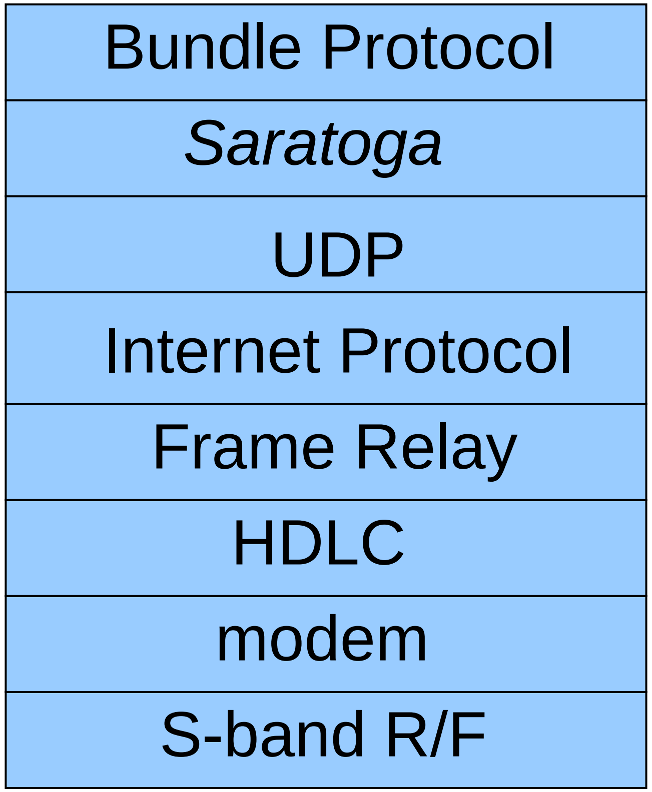
Example picture of Licklider sent to EPOXI and back

– 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’

Networking stacks used in these experiments

UK-DMC tests, Jan/Sep 2008

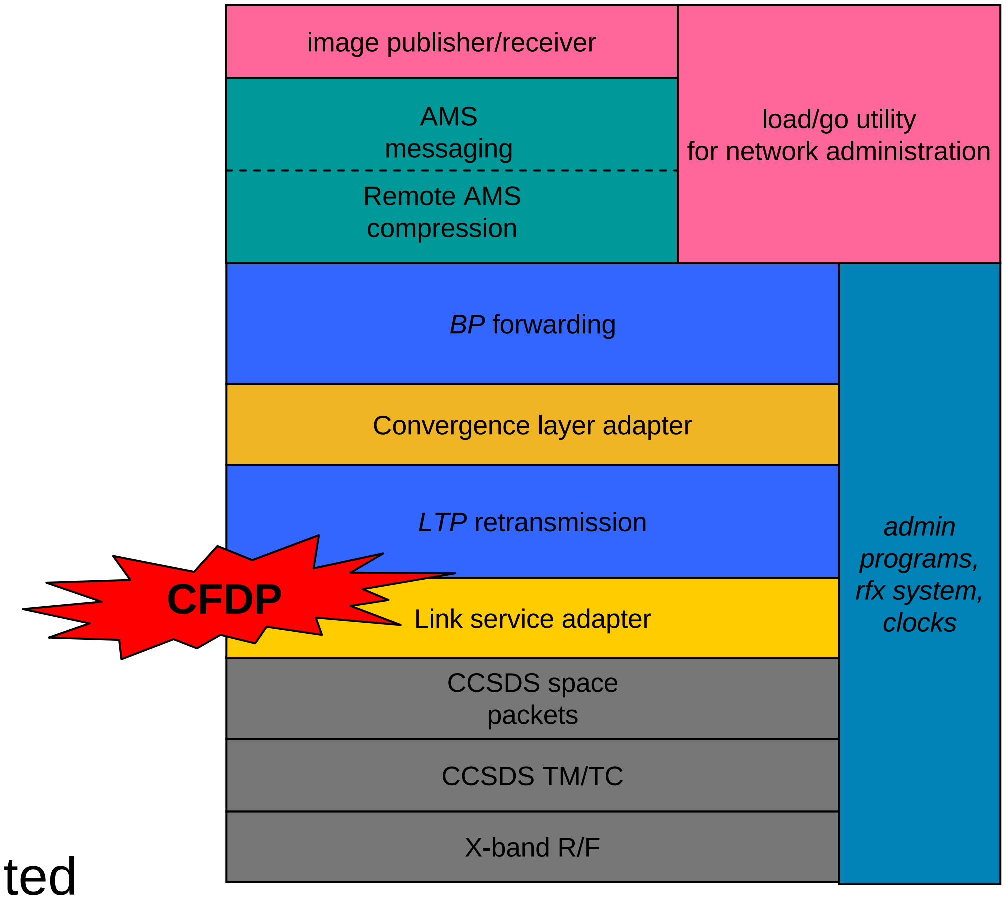
after Hogie. Max possible bundle size: 4GB



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? Application or network?

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

time

CCSDS stack world (NASA JPL) '80s-
- 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 space userbase.

Some related thoughts

- Use of standards in 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 doesn’t CCSDS want ISO-standard HDLC to 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 outside its original intended use simply unreasonable?

Interplanetary Internet *vs* intersatellite links

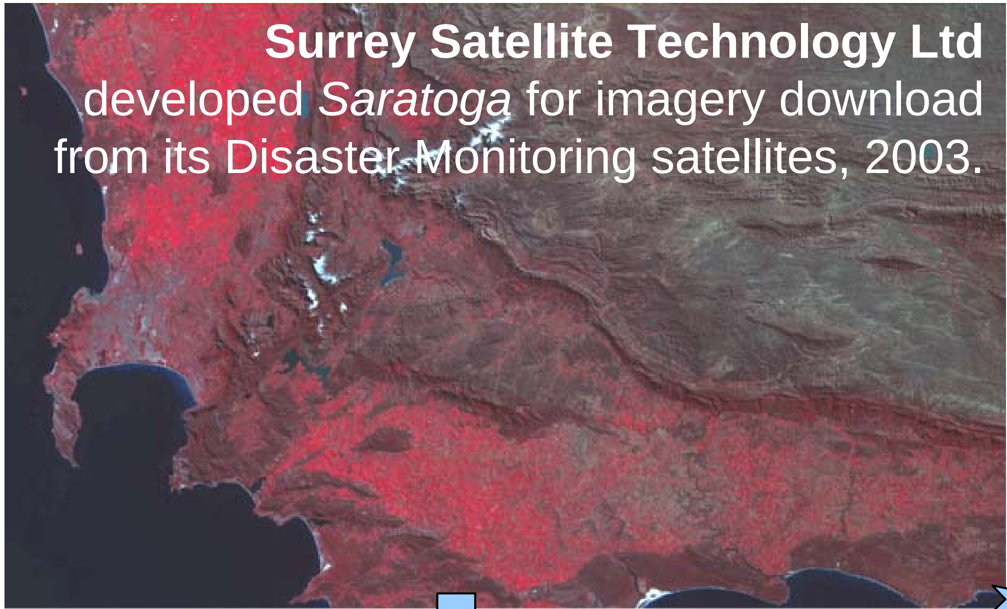
- Idea of intersatellite links has been around for years – but satellites are focused on their particular mission, don't want to waste time/money/launch mass on something unless it's clearly justified in that mission.
- Similarly, space probes are very mission-focused. Considering supporting something not in the immediate mission, with extra development cost and unclear benefits?
- The Interplanetary Internet might be a hard sell.

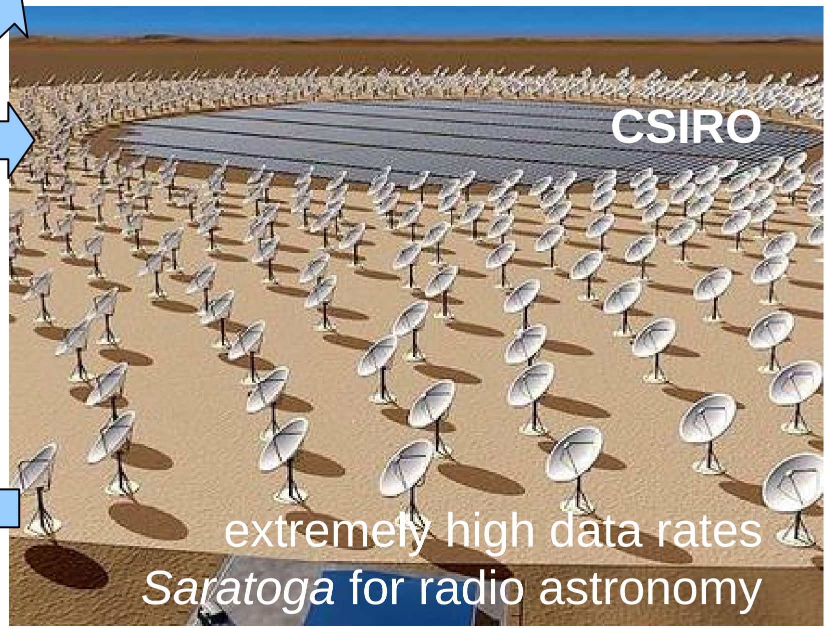
Research led to new uses for *Saratoga*

- 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?
- Solved this problem with 16/32/64/128-bit pointers and advertising capabilities.

  not needed - yet!
- 64-bit for files <16 exabytes. 128-bit: <256 exa-exabytes!
- Support for scalability and streaming introduced new users – high-speed networking for radio astronomy in Very Long Baseline Interferometers.

Saratoga development



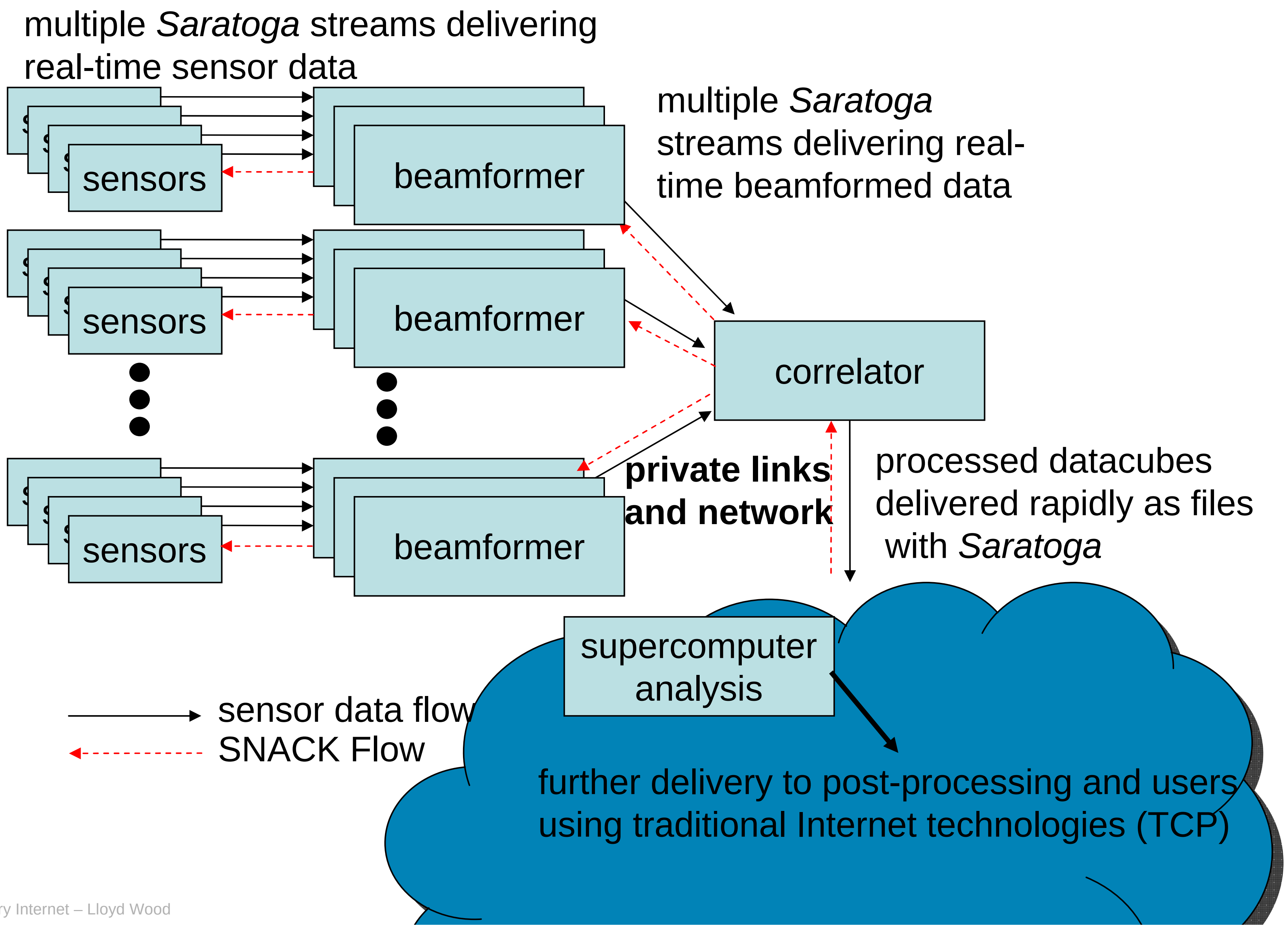


Saratoga redesigned, specified to the Internet Engineering Task Force, 2007.

NASA Glenn uses *Saratoga* onboard UK-DMC to test DTN and IPN, 2008.

Multiple *Saratoga* implementations in progress with interoperability testing.

Saratoga in the Square Kilometre Array



Saratoga for private sensor networks

- Must deliver sensor data – very quickly.
- Want to use Internet technologies – cheap, reliable, robust.
- Want more speed than TCP can offer.
- Congestion is not a problem; private single-owner managed network with scheduled traffic, single flow per link with no competition. This is not the shared public Internet!
- Support for streaming and simultaneous delivery to multiple receivers is also useful.
- Sensor capabilities are ever-increasing (side-effects of Moore's law). Need to scale for ever-growing data sizes. *Large* files. *Fast* streams.
- *Saratoga* protocol designed to meet these needs.
- Shown useful on DMC satellites. Now taking it to radio astronomy.

Some conclusions

- The Internet and the Interplanetary Internet aren't *quite* the same thing.
  - **Terrestrial Internet:** full TCP/IP suite, DNS, routing *etc.*
  - **Internet in space:** cut down, focus on UDP, much simpler.
  - **Interplanetary Internet:** DTN Bundle Protocol/CCSDS.
- We've tested the Internet in space – Hogie's serial/HDLC/FR/IP approach made that possible.
- We've used it to test the Interplanetary Internet, too.
- Technology developed for Internet in space in SSTL's Disaster Monitoring Constellation is useful in sensor networks – taking it to astronomy and the IETF.

For more information
google UK-DMC bundle

papers, presentations, videos, specifications at:
http://sat-net.com/L.Wood/dtn/

Questions?
thankyou!