NASA/GSFC Space Internet:

Extending Internet Technology Into Space

Richard Schnurr

James Rash

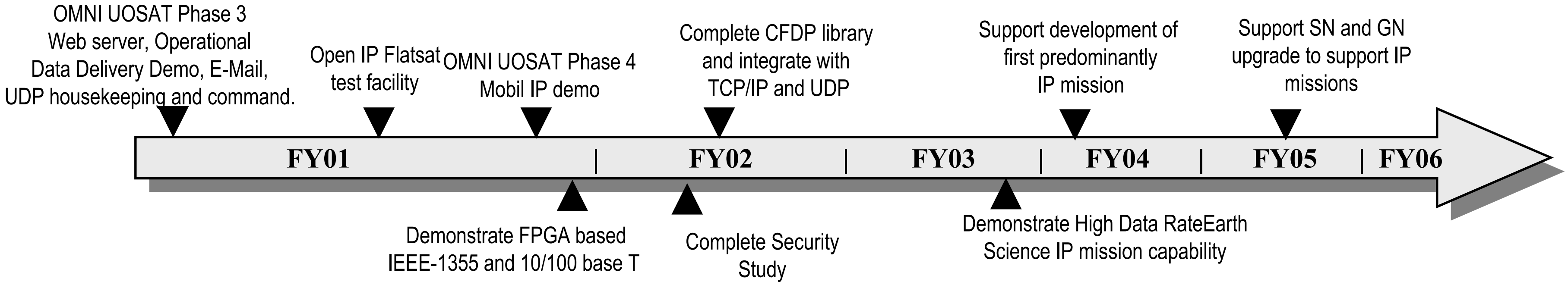
Keith Hogie

Ron Parise

Ed Criscuolo

NASA/GSFC SOMO Technology Development

Space Internet Work Area



OMNI UOSAT Phase 3
Web server, Operational
Data Delivery Demo, E-Mail,
UDP housekeeping and command.

Open IP Flatsat
test facility

OMNI UOSAT Phase 4
Mobil IP demo

Complete CFDP library
and integrate with
TCP/IP and UDP

Support development of
first predominantly
IP mission

Support SN and GN
upgrade to support IP
missions

FY01 | FY02 | FY03 | FY04 | FY05 | FY06

Demonstrate FPGA based
IEEE-1355 and 10/100 base T

Complete Security
Study

Demonstrate High Data RateEarth
Science IP mission capability

Richard Schnurr - NASA/GSFC Code 560

Rick.Schnurr@gsfc.nasa.gov
(301) 286-6069

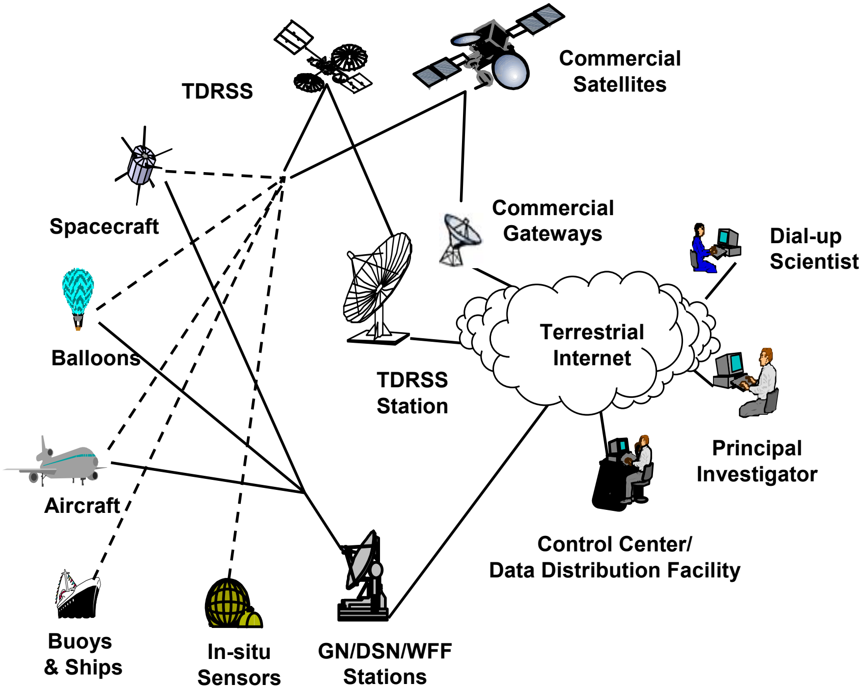
Spacecraft as an Internet Node
NASA/GSFC Work Area Roadmap

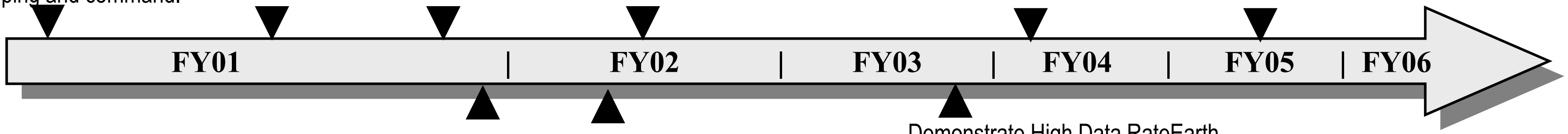
Objective

- Investigate, develop, test, and demonstrate Internet technologies that enable Space Operations vision for transparent operations for earth and space science missions.

Products

- Full IP mission Lab - Flatsat - Testing new operations concepts
- Flight Demonstration of IP operations concepts using UOSAT-12, including TCP/IP, UDP, Web servers, E-Mail, MDP, Mobil IP, VPN, IPsec
- Development of flight qualified network hardware supporting IP protocol stacks.
- CFDP Reliable file transfer library interfaced to TCP/IP and UDP
- Security studies and demonstrations
- Engineering support for infusion of IP technologies into the first IP mission.





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Program Relevance

- The application of Internet technologies to Space systems will significantly reduce the development costs for future missions while greatly increasing the flexibility of those missions. A hybrid solution including both UDP/IP and TCP/IP is envisioned.
- New distributed system and mission models are enabled
- State of the Art Application programming techniques and expertise are directly transferred to the Flight environment
- Spacecraft using IP protocols enables seamless routing of data, E-Mail, SMTP servers,Virtual Private Networking, FTP transfers, Remote File systems and Java interfaces and other custom protocols as appropriate
- Large blocks of COTS software will be directly transferable to flight platforms once NASA adopts this new way of designing space missions and hardware

The GSFC Space Internet Campaign is taking the lead to coordinate space Internet activities at GSFC. Space related industry is looking for the government to take the lead. The GSFC community is moving as quickly as possible to prototype and demonstrate these technologies and methodologies and infuse them into flight missions.

GSFC On Board Network Roadmap

- **Several LAN card developments are currently under way and should provide 100 Mega bits per second DMA capable connectivity within 2 years.**
  - JPL X2000 IEEE-1394 interface board - Flight ASICS currently in work
    - Will likely be the first flight qualified card but will be used by high end customers
  - GSFC and ESA have IEEE-1355/Spacewire activities underway
    - Flight qualified NIC cards will likely be possible in about 1 year
    - Current activity funded through breadboard
  - GSFC developing a breadboard Ethernet LAN card
  - In principle IP could be transported across standard serial or even MIL-STD-1553 interfaces
    - Current generation PPPoE systems are deployed and working.
    - PPP over serial links has existed for many years and could be used now if desired

- **On board Routers and gateways**
  - Single point routers and gateways are currently under development
    - Initial SCPS Gateway being developed for STRV mission
    - Glenn research center working with Cisco and industry on space router to support IPsec, Mobile IP, and Mobile Routing
    - GSFC & ITT are developing router for Low Power Transceiver (LPT) digital radio Shuttle flight.

- **On board Communications Technology**
  - Digital reconfigurable radios are required to allow missions developed and launched decades apart to interoperate. IP protocols would be the backbone allowing this interaction to occur.
  - Studies initiated to look at extending the LPT concept to space to space communications
  - Higher uplink rates are available whenever missions need them. No technology needs to be developed to reduce the asymmetry of the link.

Ground IP Roadmap

- **The ground already uses IP hardware. CCSDS packets are wrapped and delivered using IP.**
  - Ground system changes need further study. Many capabilities are enabled by advanced communication and the seem less connectivity of assets.
    - Mission autonomy is enabled by allowing a S/C to schedule and execute data downloads and uploads
    - The spacecraft can interact with the ground segment to optimize its data delivery and reduce overall data delivery costs
    - The spacecraft can interact with the ground data servers to enable 100% data delivery with minimum impact to the downlink channel rate.
- **Using IP will simplify the hardware needed at the ground station. The end point concept is to buy receivers with decoders included and build a simple interface between the receiver and a commercial router.**

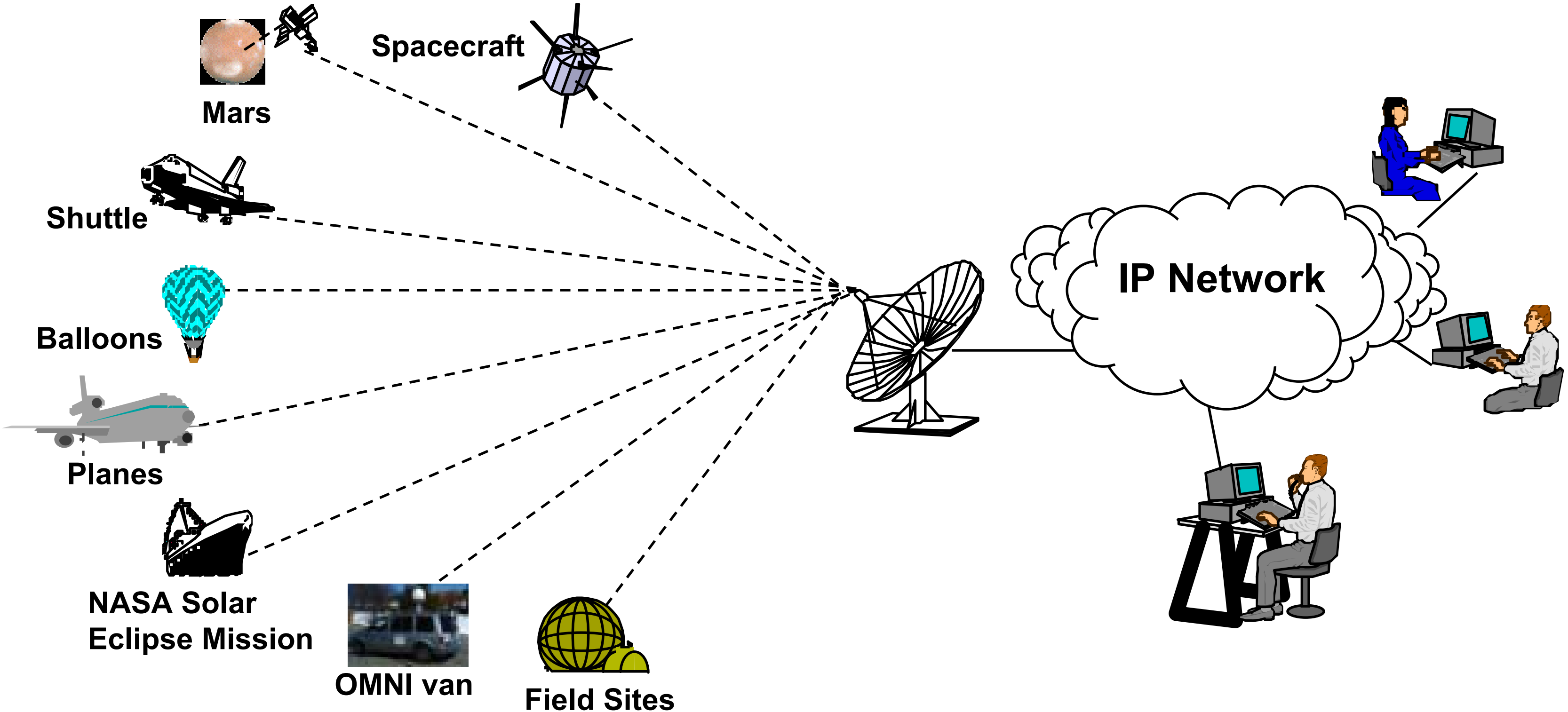
New Activities for IP in Space at NASA/GSFC

- **ESTO Funded Study Task for incorporation of SpaceWire network interface into existing Solid State Recorder Designs - PI Phil Luers, code 561**
  - Contract in process to allow up to three industry studies
- **ESTO Funded Ethernet Switch Breadboard Activity - PI Evan Webb, code 561**
  - Dovetails well with SOMO task to build and test breadboard of Flight Ethernet interface card.
- **ESTO/SOMO Funded activity to incorporate a network Router into the Low power Transceiver being developed by SOMO - PI Dave Israel, code 567.**
- **Supporting CCSDS SOIF. Standard Onboard InterFaces - P1K**

GSFC working to flight qualify hardware needed for onboard networks

Operating Missions as Nodes on the Internet (OMNI)

Architecture Concepts



Spacecraft

Mars

Shuttle

Balloons

Planes

NASA Solar Eclipse Mission

OMNI van

Field Sites

IP Network

James Rash - NASA/GSFC Code 588

James.Rash@gsfc.nasa.gov
(301) 286-5246

OMNI Concepts

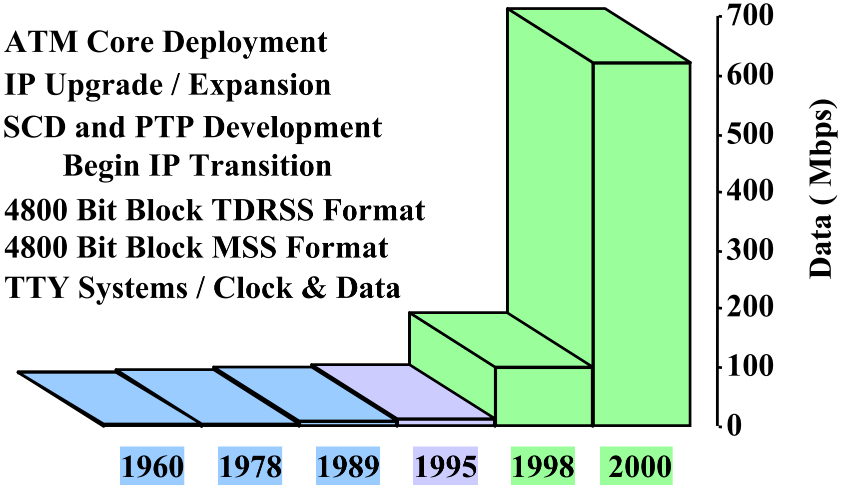
- **End-to-end layered subsystems with industry-standard networking interfaces**
  - Multiple vendor solutions and competition
  - Simplified future upgrades
  - Simplified designs -- modularized into smaller subsystems
  - Simplified Interface Control Documents (ICDs) -- if needed at all
- **Isolating "space specific" issues to the physical layer -- Important**
  - Continued use of existing antennas & RF equipment
  - Simplified front-ends
  - Cleaned up RF link -- standard networking interfaces for transmitter/receiver
- **Standard off-the-shelf WAN technology and comm equipment**
- **Satellite mobility via standard Internet mobile network solutions**
- **UDP where needed as an alternative to TCP**
- **Capitalizing on existing NASA infrastructure and Nascom evolution that has built an operational IP backbone out to all ground stations**

Industry Standards and Off-the-Shelf Solutions

Case Study - Nascom Upgrades

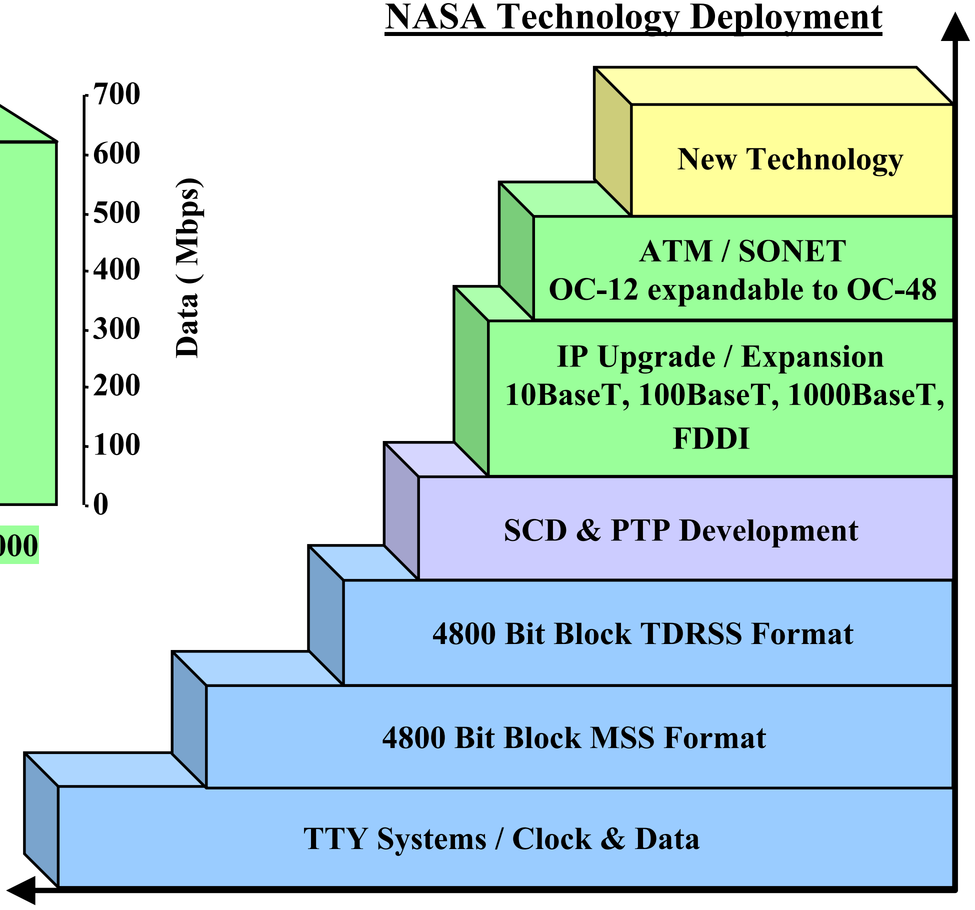
NASA Network Backbone Capacity

(2000) ATM Core Deployment
(1998) IP Upgrade / Expansion
(1995) SCD and PTP Development
Begin IP Transition
(1989) 4800 Bit Block TDRSS Format
(1978) 4800 Bit Block MSS Format
(1960) TTY Systems / Clock & Data



🟨 Future
🟩 Standards Based Systems
🟪 Transition Systems
🟦 Legacy Systems

NASA Technology Deployment



New Technology

ATM / SONET
OC-12 expandable to OC-48

IP Upgrade / Expansion
10BaseT, 100BaseT, 1000BaseT,
FDDI

SCD & PTP Development

4800 Bit Block TDRSS Format

4800 Bit Block MSS Format

TTY Systems / Clock & Data

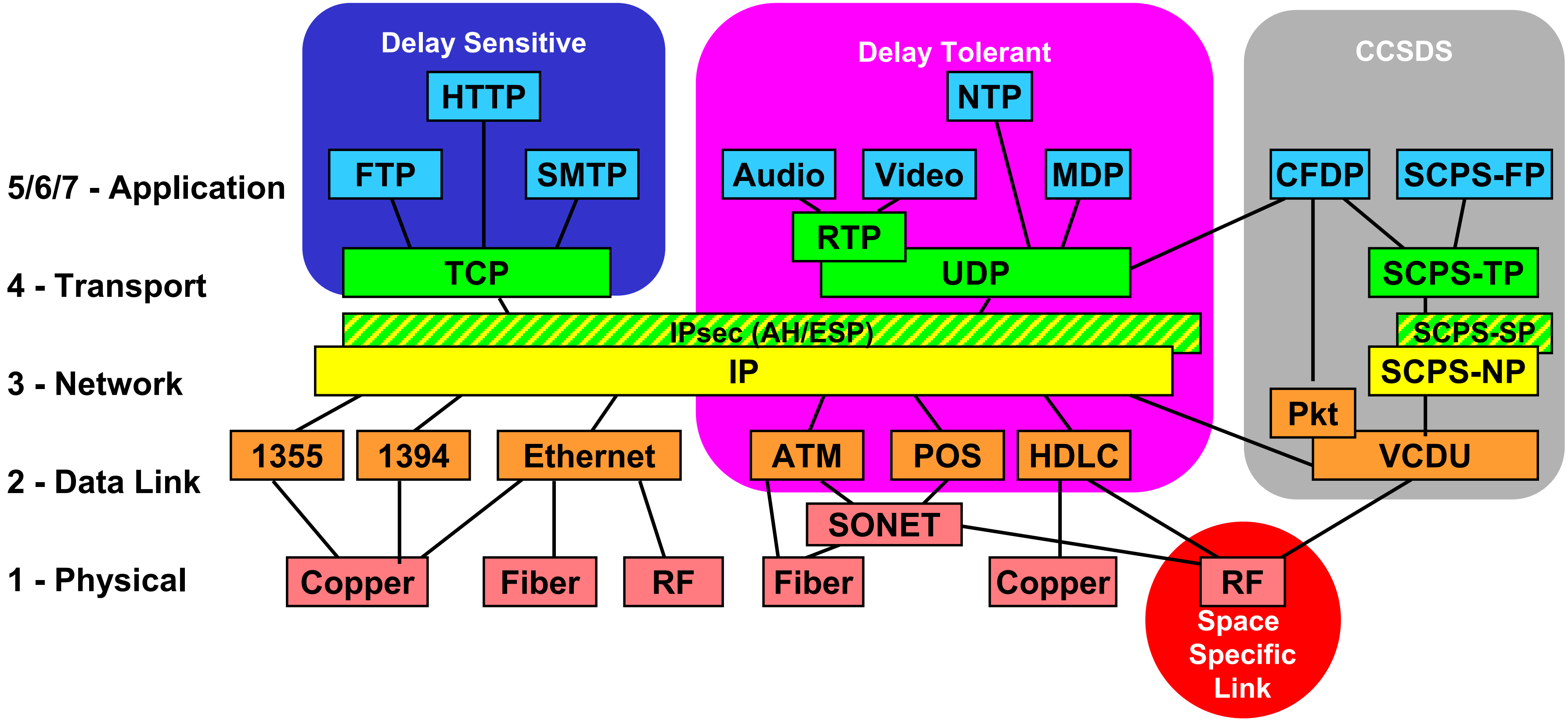
Transitioning legacy 4800 bit block protocol to an IP infrastructure .

Case Study - Nascom Success

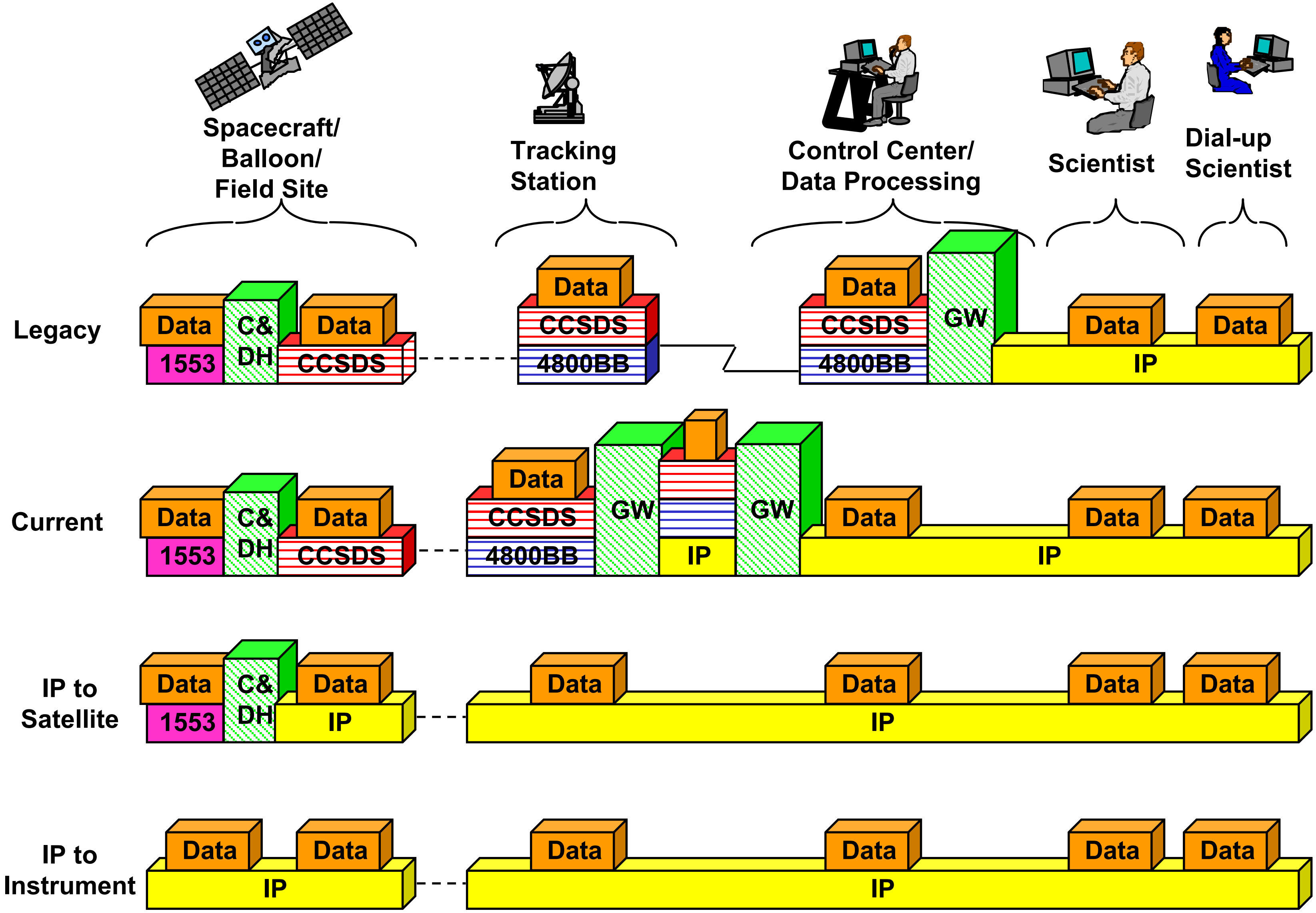
- **Old systems - staff of 70 programmers to develop and maintain systems**
  - MSS - Message Switch System
  - CSS - Circuit Switch System
  - DCS - Digital matrix switch Control System
  - MDM - Multiplexor DeMultiplexor
  - MACS - MDM Automated Control System
  - DLMS - Data Link Monitor System
  - Statistical Mux
  - Tech Control
- **After IP Transition - staff of 5 programmers**
- **Operations staff also reduced after consolidating systems**
  - Conversion Device Manager
  - IP Network Operation Center
  - Tech Control
- **Upgrading Nascom backbone to higher rates is now much easier using commercial equipment**
- **IP backbone now available for future missions**

Layers Are Critical

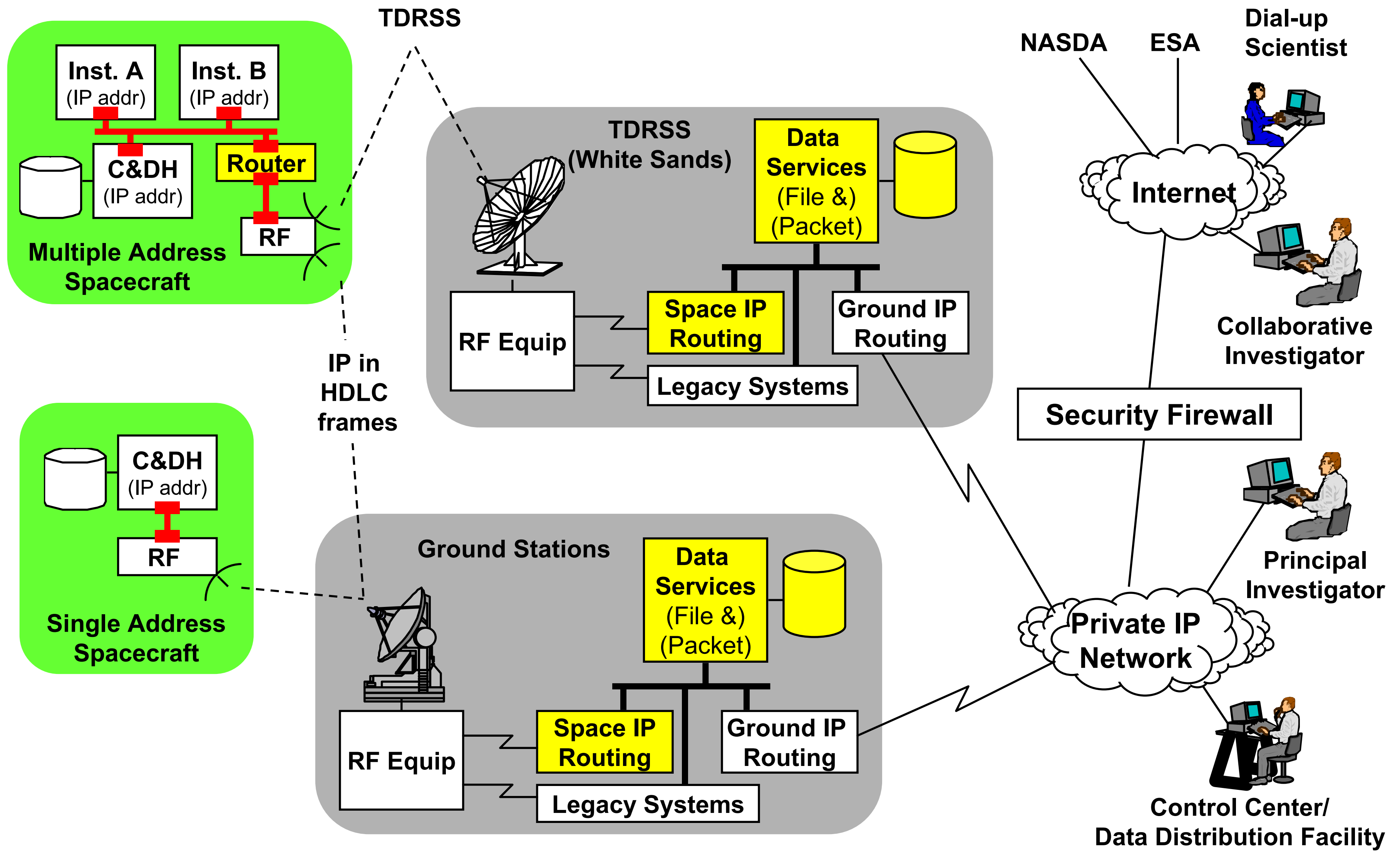
- **Clean, layered approach is critical:**
  - Isolate special space problems so they can be addressed as needed
  - Allows independent implementations
  - Modularity allows upgrading individual areas



End-to-End Space Link Evolution



Space Internet Implementation



Current OMNI Work

- **Continue developing “FlatSat” Testbed capabilities**
  - Digital WAN channel simulator -- errors & delay up to 51 Mbps
  - RF channel test equipment (TURFTS)
  - Routers, hubs, 10/100 Ethernet
  - LAN and WAN analyzers
  - Sun, PC, Mac, PC104, cPCI computers
  - Solaris, Windows 2000, Linux, MacOS, VxWorks operating systems
- **Investigate more protocols and operation scenarios in “FlatSat” Testbed**
  - Linux on UoSAT-12 onboard processor (20 Mhz 386 processor)
  - UDP file transfer protocols (MDP, CFDP)
  - Mobile IP
  - Internet security
  - Mobile Routing
- **Test selected protocols in space on UoSAT-12 spacecraft**
  - Migrate successful FlatSat work to space
- **Continue working with missions and vendors**
- **Prepare for high-rate (150 - 600 Mbps) “FlatSat” tests in FY02**

Key Issues for Future NASA Missions

- **Basic communication issues (not protocol related)**
  - Higher data rates, longer distances, RF vs Optical, crosslink comm
- **Mission complexity**
  - More spacecraft, more complex communication topologies
- **Non-technical issues**
  - Less resources, shorter schedules
- **More complex operations concepts require new approaches**
- **Current spacecraft communications are very manpower intensive and highly scheduled -- automation is necessary to reduce costs**
- **Necessity to shorten design/development -- more off-the-shelf hardware and software**

Goal: simplest, most cost-effective delivery of science data when & where needed

Key Components for IP in Space

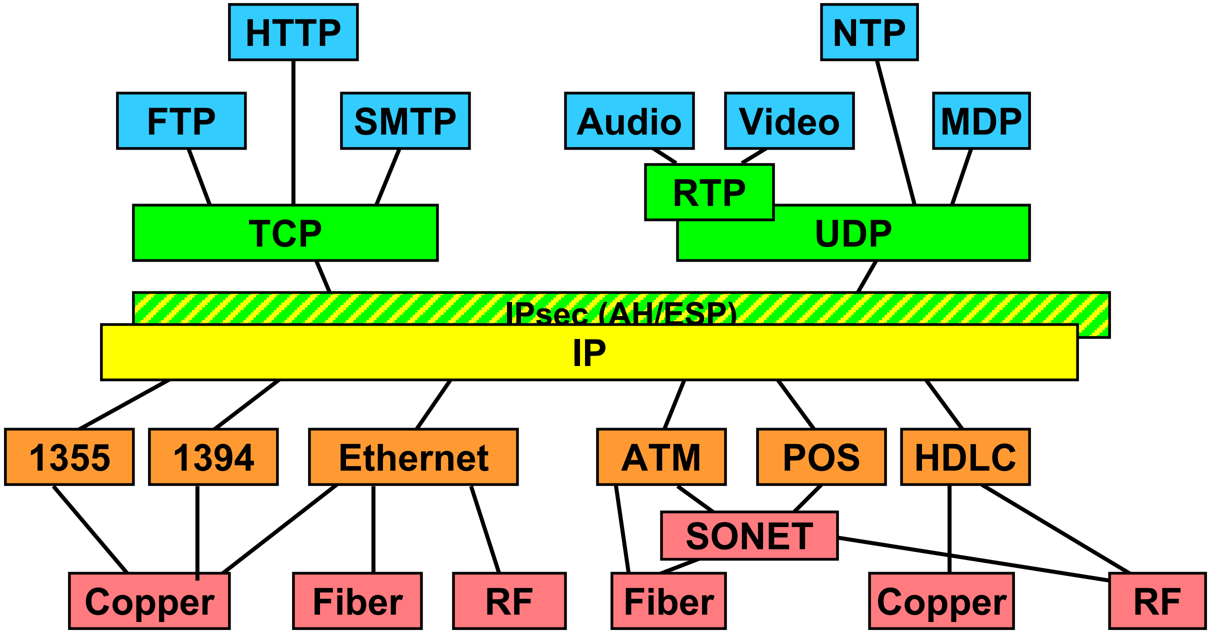
- **Radiation hard onboard LAN components**
  - Ethernet, 1355 - Spacewire , 1394 - Firewire
- **Radiation hard onboard serial interfaces**
  - HDLC, ATM, Packet over SONET
- **Ground based FEC coding front-ends**
  - GRID, COTS satellite modems
- **Smaller, lighter, cheaper, reconfigurable transceivers**
  - LPT, cell phone technology, wireless Ethernet
  - Frequency reuse
  - Dynamic power management

Executive Summary

- **Key to improving cost-effectiveness of future missions**
  - Commodity-level industry standards
  - Off-the-shelf software & hardware
- **Technically, IP works fine in space**
  - No show-stoppers: what remains is just standard engineering
  - Engineering solution space enlarged
- **Organizationally, it enables a new way of doing business**
  - Budget profile changes (more science per dollar)
  - Enables advanced mission concepts (e.g., collaborative science)
  - Better alignment with industry standards and products
  - Simpler overall mission designs and operations enabled
- **Remaining issues**
  - Security studies under way -- results due by October 2001
  - Space qualified onboard LAN hardware, serial interfaces, transceivers
  - Ground system upgrades

Operating Missions as Nodes on the Internet (OMNI)

Technical Details



Keith Hogie - Computer Sciences Corp

Keith.Hogie@gsfc.nasa.gov
(301) 794-2999

Technical Challenges of Space Communication

- **RF Issues**
  - Constrained power, mass
  - Antenna size, gain, pointed/omni
  - Frequency and bandwidth allocation
  - Physics - Weak signals, 1/r**2, achievable data rates
  - Fade, multipath, interference
  - Error rate

- **Bandwidth/Delay**
  - Asymmetric data rates - adjustable during design
  - Delay - fixed function of the orbit (unless we make signals propagate faster than light)

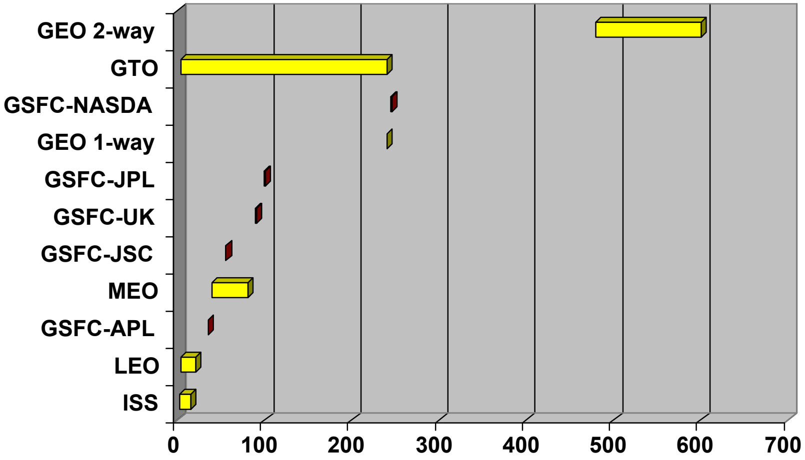
- **Connectivity/Topology**
  - Possibly unidirectional link
  - Link discontinuity
  - Lack of communication infrastructure in space

- **Same issues for any protocol (TDM, CCSDS, IP) - space is space**

Internet and Space Delay Comparison

- **Many space propagation times are less that on the Internet**

Orbit	Distance (Km)	Light Speed
ISS	400 - 2000	3 - 15 ms
LEO	600 - 3000	4 - 20 ms
MEO	6000 - 12,000	40 - 80 ms
GEO 1-way	36,000	240 ms
GEO 2-way	72,000	480 ms
Lunar	384,000	2.6 sec
L1/L2	1,500,000	10.0 sec
Mars	78M - 376M	9 - 50 min.



Internet	Distance (Km)	Light Speed RTT	Measured Round Trip Time
GSFC-APL	32	.212 ms	35 ms
GSFC-JSC	1600	10.6 ms	55 ms
GSFC-JPL	4000	26.6 ms	100 ms
GSFC-UK	5800	28.6 ms	90 ms
GSFC-NASDA	10,700	71.4 ms	245 ms

Space Link Errors

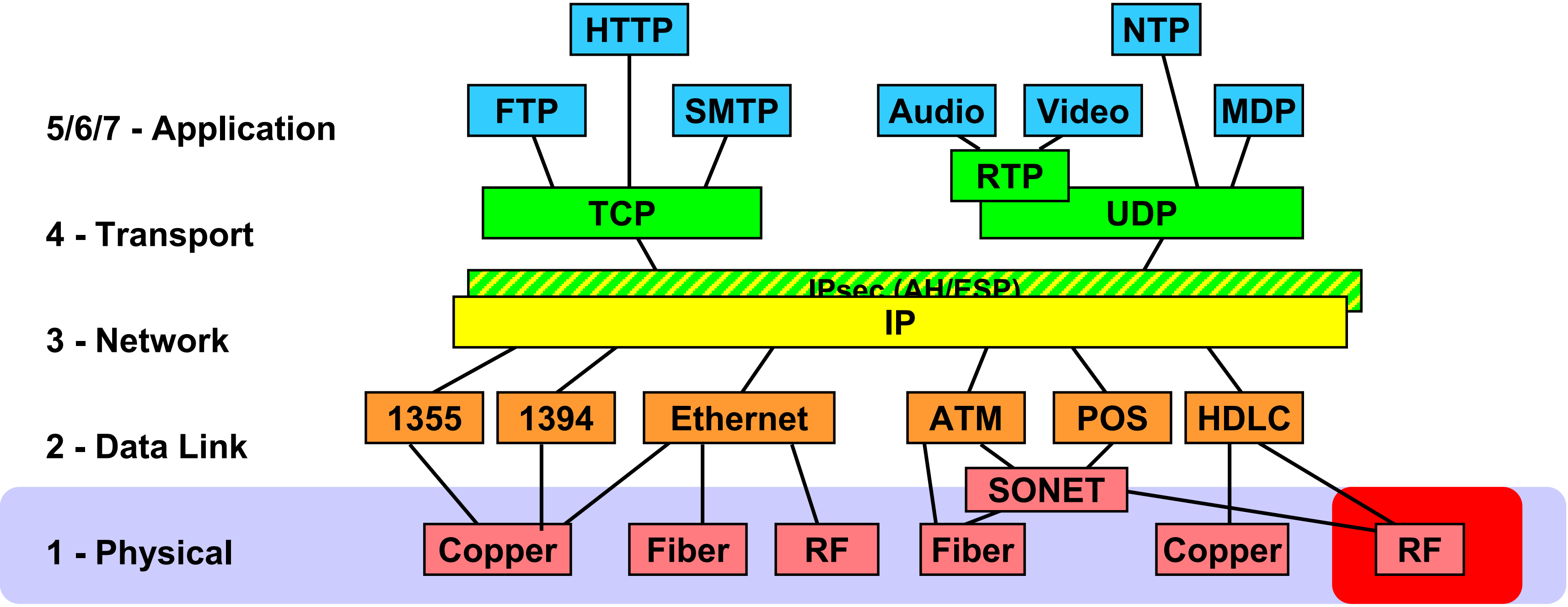
- **Space links have always needed to be reasonably error free (after FEC) in order to deliver useful science data**
- **Frame loss and approximate BER for WIND and POLAR missions**
  - Data received through DSN stations
  - Outer Reed/Solomon coding
  - Telemetry in 256 byte TDM frames
- **Scientists would not accept data with actual 10^{-5} BER**

File	MB	Blocks	Frames	Drop Lock	Error rate
WIND - EI2001009	106	177,791	388,335	16	2.01E-8
WIND - EI2001013	99	166,134	359,390	16	2.17E-8
WIND - EI2001014	60	100,009	203,751	10	2.40E-8
WIND - BI	10	16,550	37,089	2	2.63E-8
WIND - BI	6	10,396	23,295	2	4.19E-8
WIND -	55	91,070	219,131	9	2.01E-8
POLAR - BI2001016	29	48,081	107,790	2	9.06E-9
POLAR - NRT			600,000	20	1.63E-8
WIND - NRT			218,000	12	2.69E-8
UARS (TDRSS)			49,671	0	0
ERBS (TDRSS)			58,321	1	1.07E-10

Frame errors at 10^{-5} BER
7,953
7,360
4,173
760
477
4,488
2,208
12,288
4,465
508
933

Physical Layer

- Mechanism for delivering bits across media (e.g. copper, fiber, RF)
- Trade-off power, antenna gain, distance, noise, data rate, modulation, freq.
- Main issue is making space RF or possibly Optical link deliver bits
- RF system must be built for space and is independent of upper layer protocols

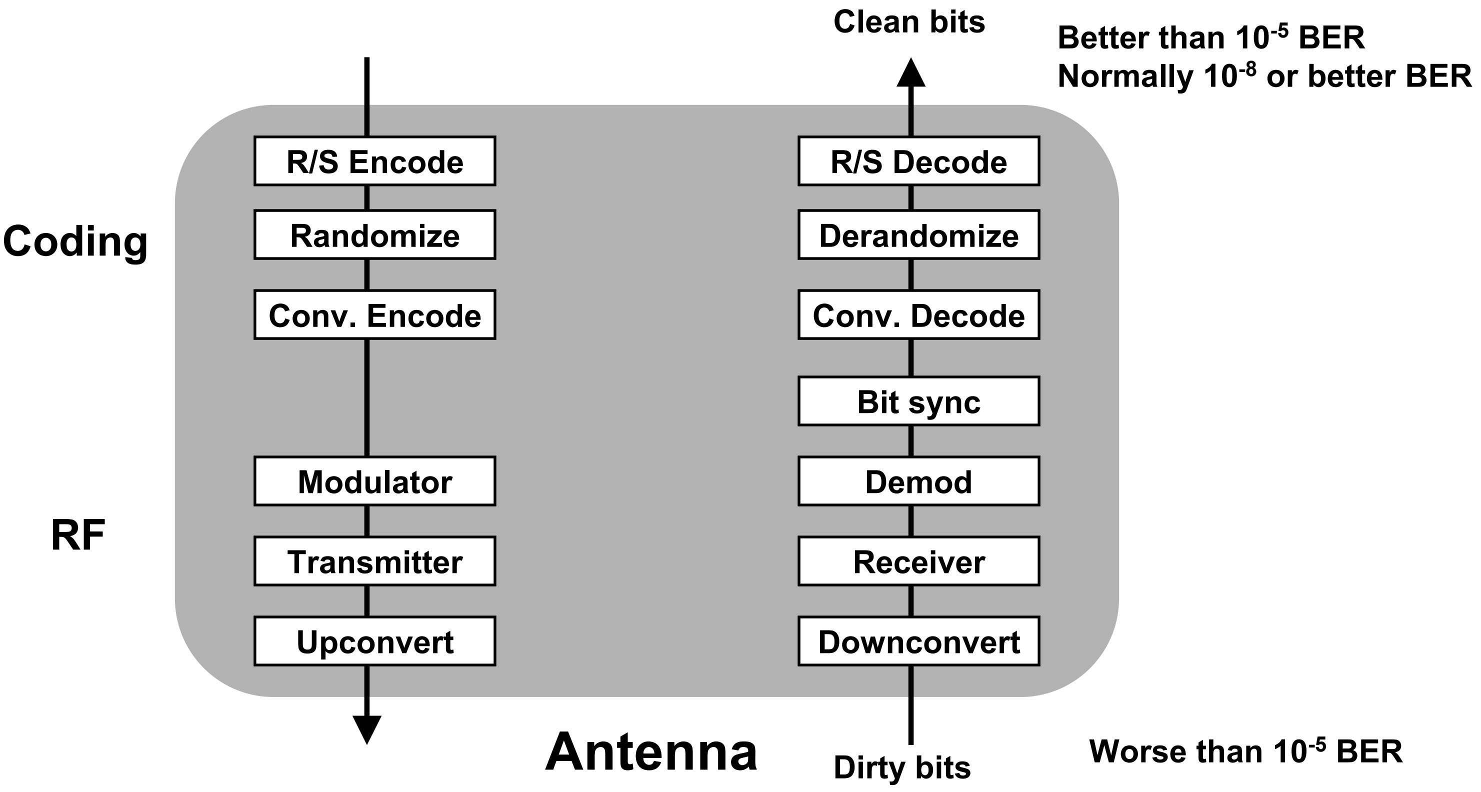


Space Physical Layer Issues

- **Basic challenge is delivering bits at needed rate across distance**
  - Antenna size/gain, omnidirectional/pointed
  - Transmitter/receiver frequency, modulation, power, mass,
  - Doppler compensation, interference, fade
  - Forward error coding
- **International agreements on frequency allocation and clearance**
- **Noisy RF links require forward error correction**
  - Convolutional
  - Reed/Solomon
  - Reed/Meuller
  - Turbo codes
- **Constellations**
  - Frequency reuse among nodes
  - Link establishment among constellation nodes
- **Physical layer issues can and should be handled completely independent of upper layer protocols**
- **This is a “space specific” area**

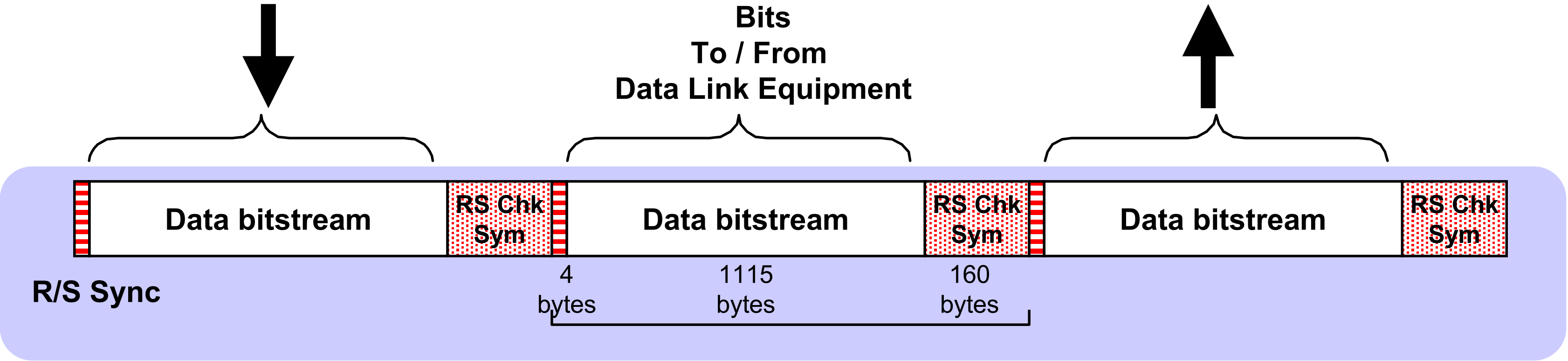
RF Link Bit Level Operations

- **All NASA missions (Earth orbit and Deep Space) design their RF systems to provide 10^{-5} or better BER after physical link coding**
- **After coding, most links operate at 10^{-8} or better**
- **Scientists would not accept the data recovered with a 10^{-5} BER**



RF/Physical View of Data Link

- **Noisy communication links like space need special handling - primarily forward error correction (FEC) to clean up noise/errors in the bitstream**
  - Convolutional coding - bit level FEC
  - Reed/Solomon coding - block level FEC
  - Block code FECs use long sync pattern (4 bytes) - helps find unique pattern
  - Fixed length frames - allow “flywheeling” to recover frames with damaged sync pattern



Physical Link Coding

Physical Link

- **RF mod/demod**
- **Up/down convert**
- **Bit sync**

- **Convolutional encode/decode**
- **Randomize/derandomize**
- **Reed-Solomon encode/decode**

Commercial Uses of Reed/Solomon FEC

- **Reed-Solomon coding used to clean up bitstreams everywhere**
  - Storage devices - Compact Disc, DVD, barcodes
  - High-speed modems (ADSL, xDSL, cable modems)
  - Wireless and mobile communications (cell phones, microwave links)
  - Digital television (DVB)
  - Satellite communications (satellite modems)

- **Other options such as convolutional coding are also used alone and in combination with Reed-Solomon**

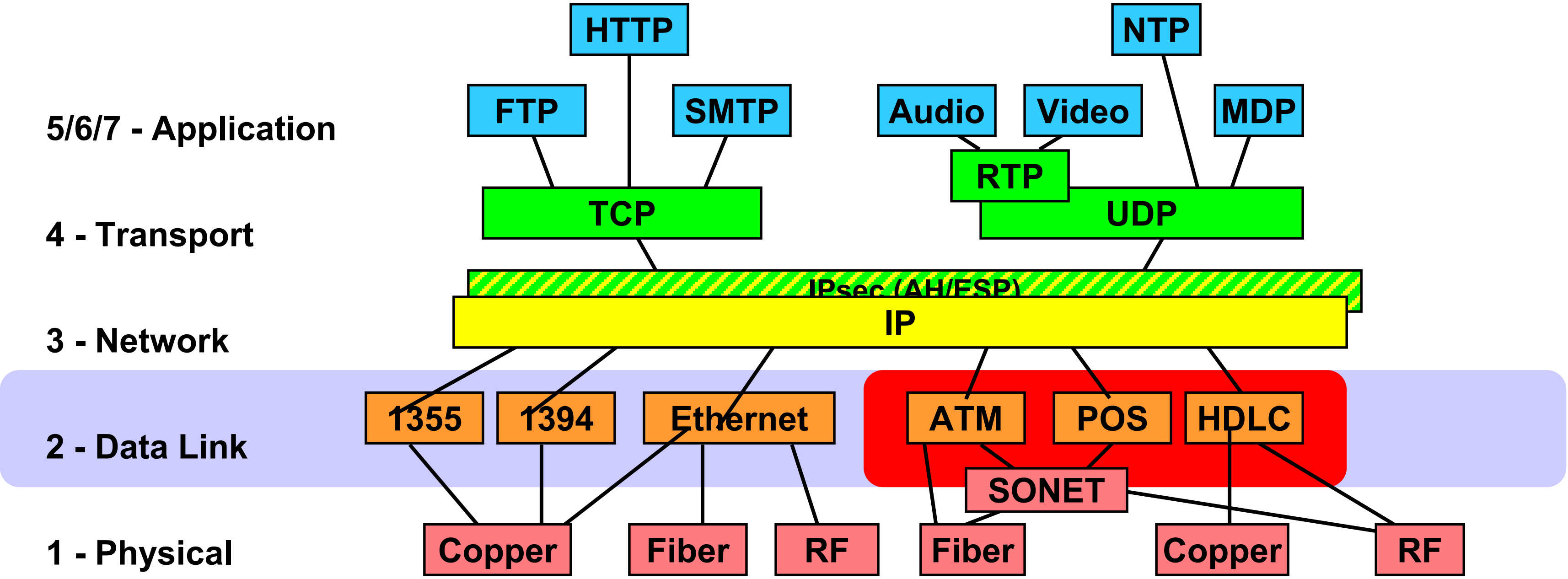
- **In all of these applications the Reed-Solomon coding is independent of the upper layer framing mechanisms**

- **FEC just cleans up the bitstream and operates at a bit-level interface**

- **Different applications use different Reed-Solomon codes selected to meet their specific error characteristics**

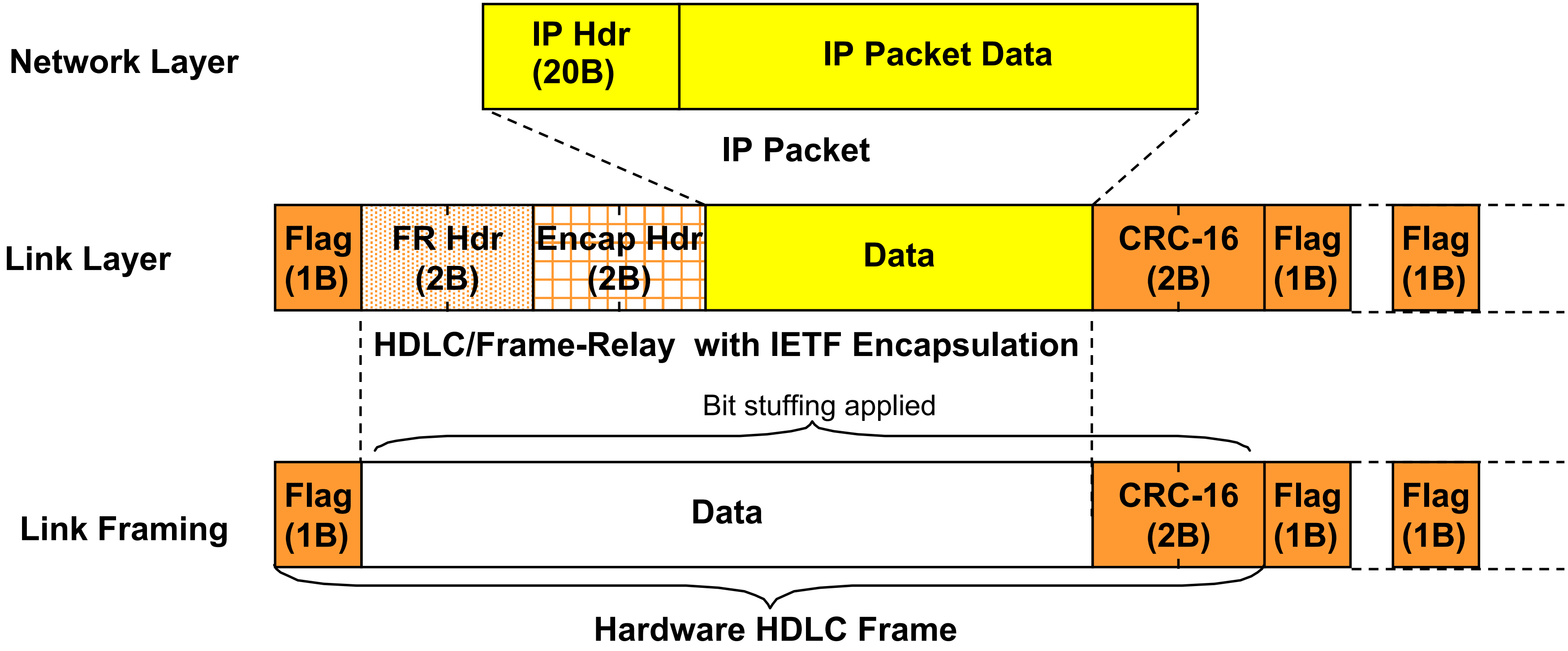
Data link Layer

- **Transmit**
  - Frame upper layer protocol data units over the physical layer
  - Add error detection to transmitted frames
- **Receive**
  - Extract frames from physical layer and pass up
  - Perform error detection on received frames



HDLC Space Link Data Framing

- **IETF Multi-Protocol Encapsulation over Frame Relay (RFC 2427)**
  - Uses Frame Relay/HDLC - Not X.25 or LAP-B
  - No windowing or flow control - completely independent of delay
- **HDLC FLAG bytes (01111110) between frames - no fill frames or packets**
- **Bit stuffing to mask FLAG patterns in data**



HDLC Bit Stuffing Overhead

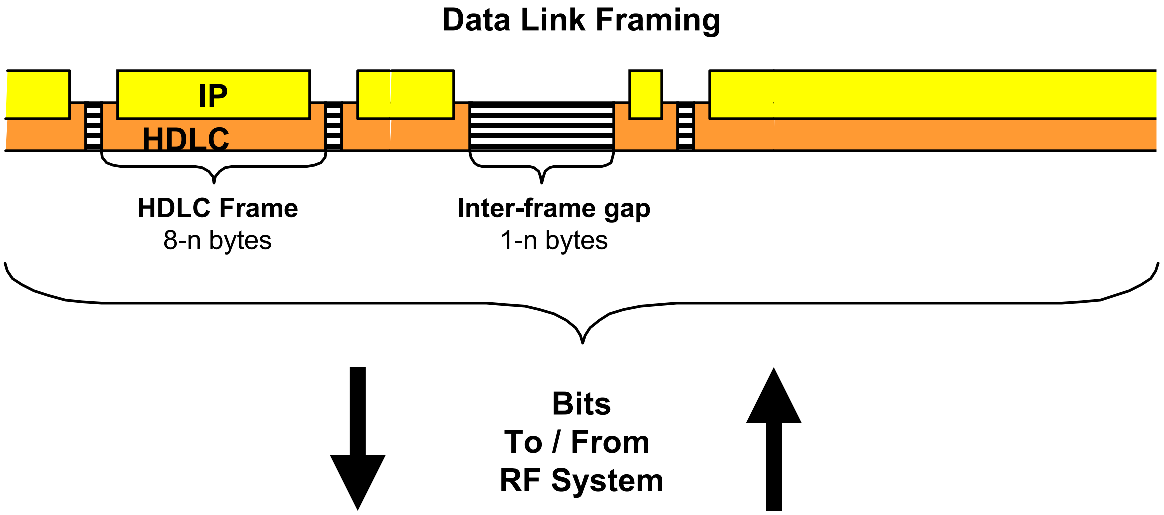
- Effect of HDLC bit stuffing on sample science data (WIND, POLAR, SOHO)

File	MB	Total Bits	Stuffed Bits	Overhead
WIND - EI2001009	103	820,163,520	7,321,191	.89 %
WIND - EI2001013	95	759,031,680	7,322,842	.96 %
WIND - EI2001014	54	430,322,112	4,125,045	.96 %
WIND - BI	10	78,331,968	697,327	.89 %
WIND - BI	6	49,199,040	432,996	.88 %
WIND -	58	462,804,672	4,135,223	.89 %
POLAR - BI2001016-72054	30	240,021,120	1,715,776	.71 %
POLAR - BI2001016-72117	31	248,787,072	1,635,811	.66 %
POLAR - BI2001016-72233	20	162,061,056	1,092,277	.67 %
POLAR - BI2001016-72056	153	1,228,237,440	13,663,206	1.11 %
POLAR - BI2001016-72118	172	1,380,528,384	13,502,480	.98 %
SOHO - 01-13T00	254	2,032,283,904	22,445,559	1.10 %
SOHO - 01-13T01	61	490,085,376	3,702,294	.76 %
SOHO - 01-13T02	28	222,693,888	2,182,177	.98 %
SOHO - 01-13T07	258	2,069,539,200	18,621,370	.90 %
SOHO - 01-13T08	66	525,558,528	5,699,767	1.08 %
SOHO - 01-13T09	44	352,356,096	5,699,767	1.03 %
	1,443	11,552,005,056	111,939,731	.97 %

Router View of Space Link

Link Framing

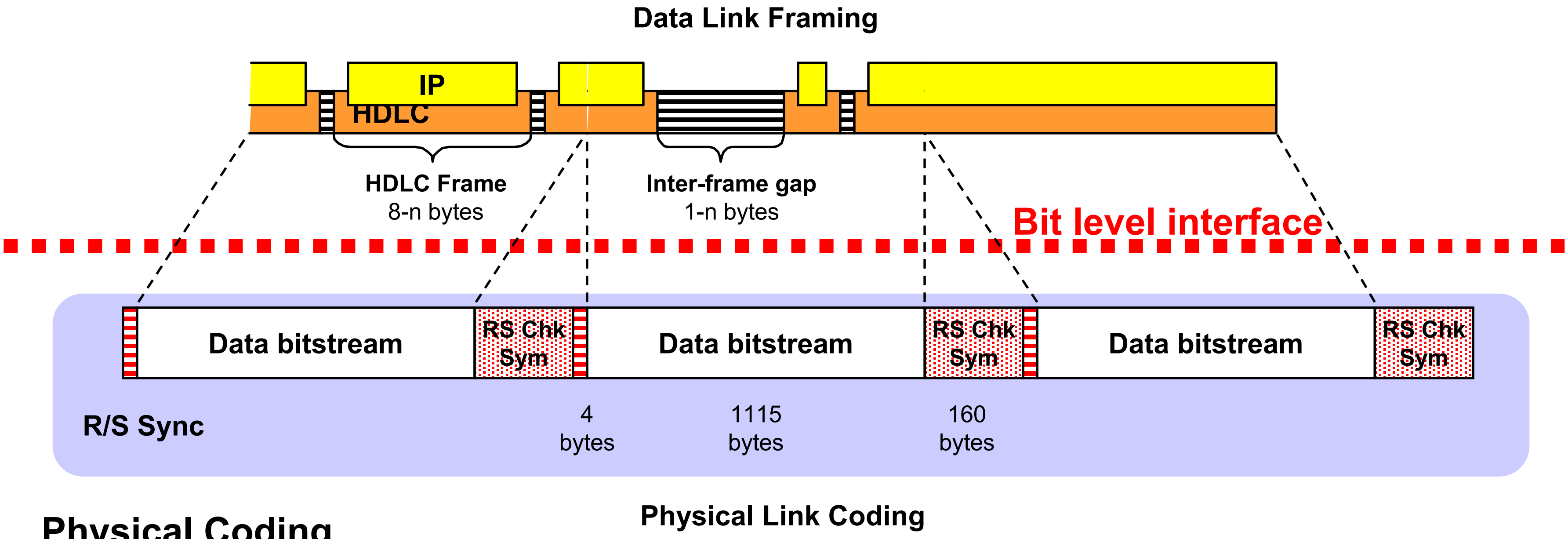
- Locate data frames
- Error check data frames
- Link level addressing
- Send FLAGs between frames (no fill frames or packets needed)


Data Link Framing

Separation of Coding and Framing

Link Framing

- Locate data frames
- Error check data frames
- Link level addressing



Data Link Framing

Physical Link Coding

Physical Coding

- RF mod/demod
- Up/down convert
- Bit sync

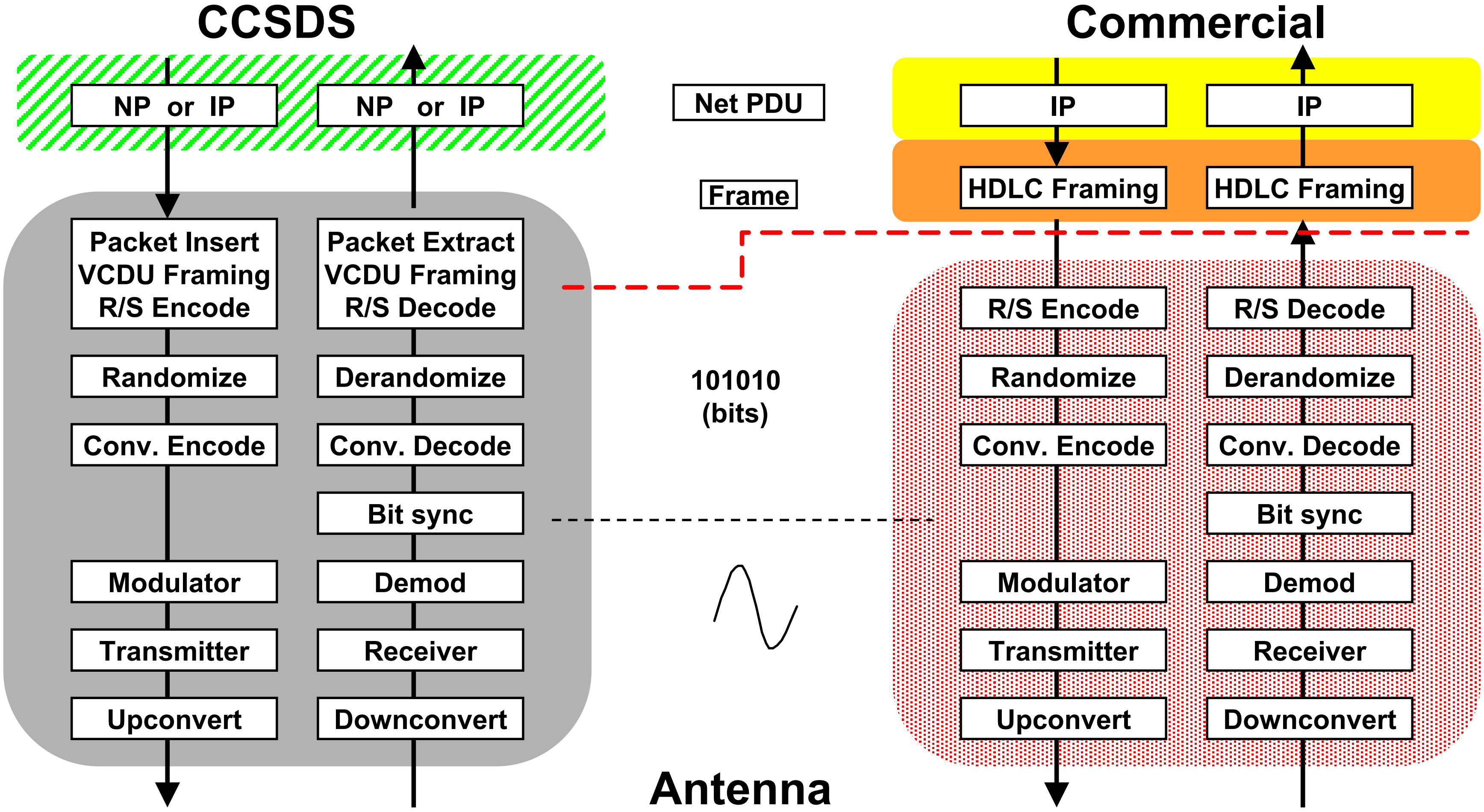
- Convolutional encode/decode
- Randomize/derandomize
- Reed-Solomon encode/decode

Cisco Approach to Space Links

- In 1995 we asked Cisco about implementing Reed/Solomon and CCSDS frame/packet handling in their programmable router interface cards
- Cisco responded indicating that they did not see a viable market there for them
- They also indicated that the standard approach is to use a "satellite modem" to deal with space link specific details
- Satellite modems consist of combinations of Reed/Solomon coding, convolutional coding, randomization, and RF modules
- Satellite modems are widely used to deploy Internet connections across satellite links around the world

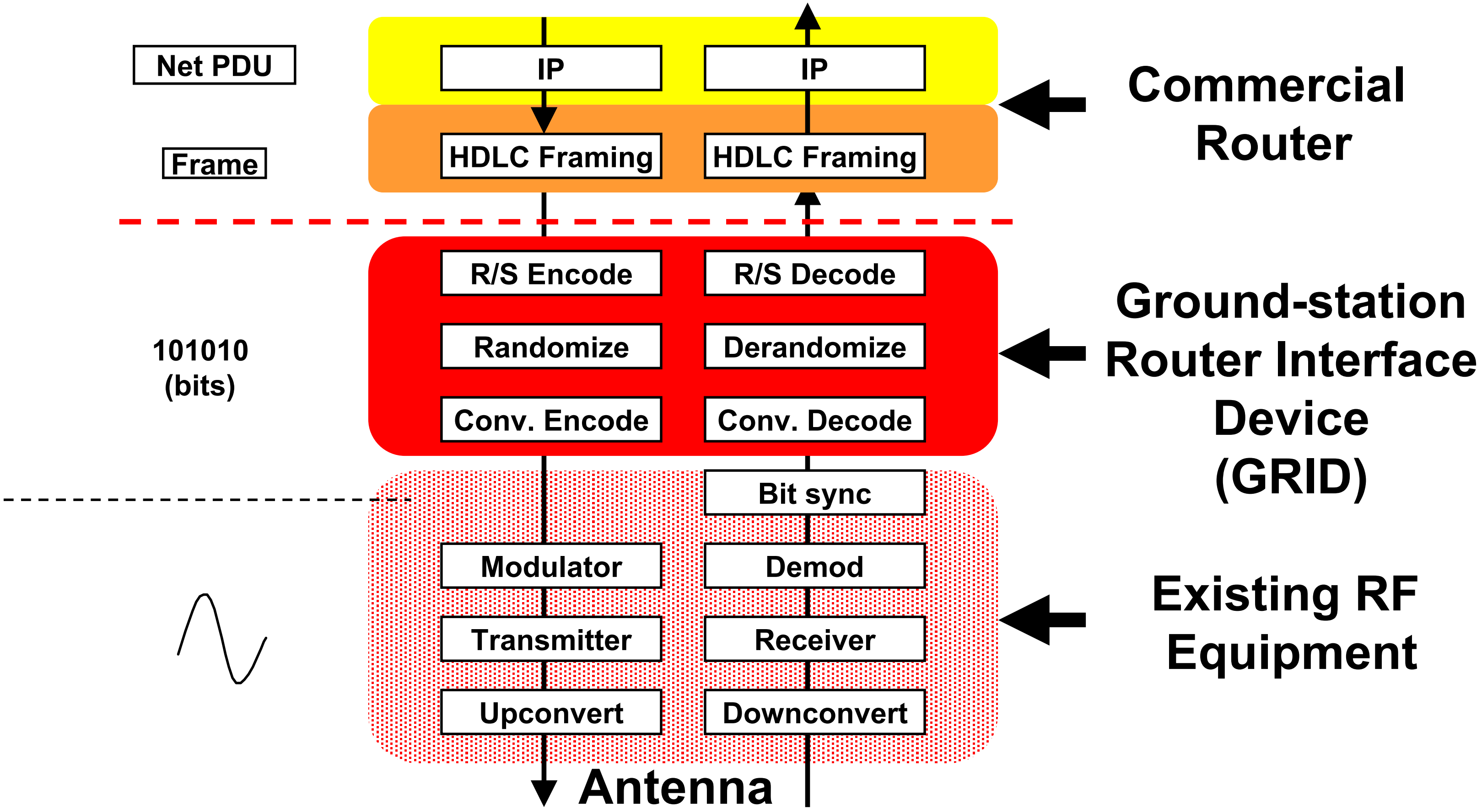
CCSDS vs Commercial Layering

- Very similar except commercial world separates FEC and framing

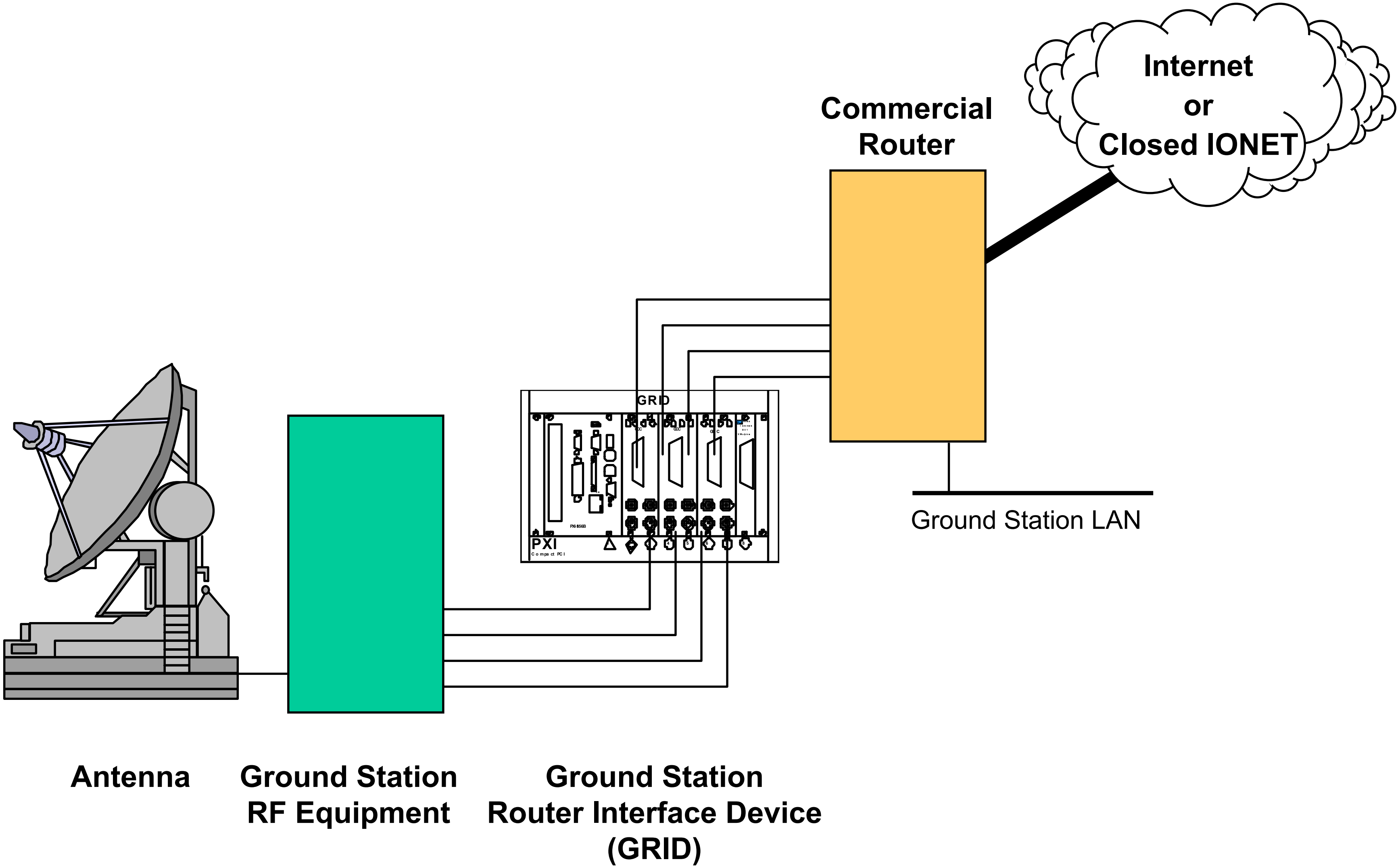


IP Interface for Existing RF Equipment

- A device similar to a commercial satellite modem is needed to connect NASA RF interfaces to commercial routers



GRID Ground Station Installation



GRID Features

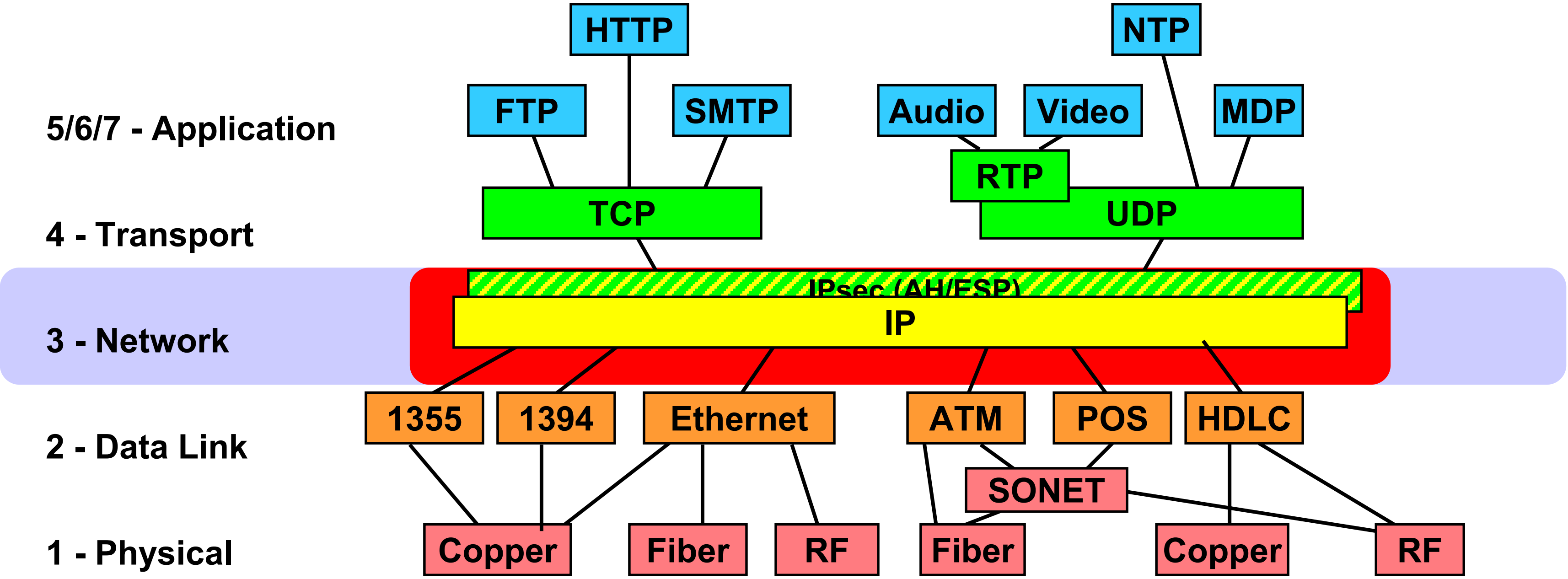
- **Provide a cheap and simple interface converter between existing RF equipment at ground station and commercial router interfaces**
- **Only operates on coding and signal levels, no knowledge of data link framing formats**
- **Provide multiple router serial port connections and configurations in a single chassis.**
- **Allow ground stations to connect their command and telemetry data systems to a standard COTS router.**
  - COTS Routers do not provide any channel coding/decoding functions, etc.
  - Most ground stations do not provide standard serial port interfaces to the command and telemetry systems
- **Allow automated configuration from an external computer and provide Data Quality Monitoring status on links.**

Onboard LANs

- **Eventually each spacecraft instrument may be on a LAN with its own IP address**
- **Building science instruments using common LAN interfaces would greatly simplify integration and test**
- **Current LAN options being investigated**
  - IEEE-1355
  - IEEE-1394
  - Ethernet
- **Ethernet becoming major industrial LAN technology supporting real-time, deterministic environments**
  - Industrial Ethernet Association - http://www.industrialethernet.com/
  - Industrial Automation Open Networking Alliance - http://www.iaona.com/
  - GE Cisco Industrial Networks - http://www.gecisco.com
- **Lots of hardware and support tools for Ethernet LANs**

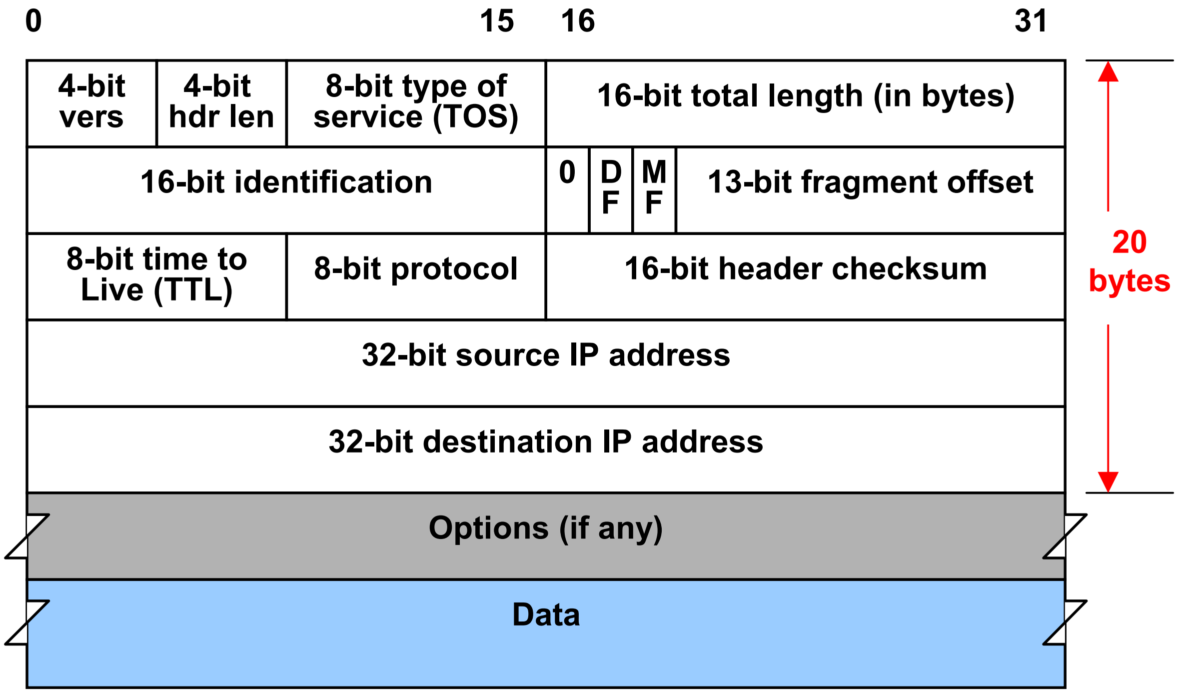
Network Layer

- Provides global, end-to-end addressing for each data packet
- IP packets forwarded by routers
- Automated management of routing tables
- Implemented in routers and end-system operating systems
- Key to the success of the Internet



Network Layer Protocol

- Fixed format protocol header - follow it exactly or you don't communicate
- Standard, fixed format header is the key to global interoperability
- IP hides the details of the data link layers from the upper layer protocols



<table>
<tr><td>0</td><td></td><td>15</td><td>16</td><td></td><td></td><td>31</td></tr>
<tr><td>4-bit vers</td><td>4-bit hdr len</td><td>8-bit type of service (TOS)</td><td colspan="4">16-bit total length (in bytes)</td></tr>
<tr><td colspan="3">16-bit identification</td><td>0</td><td>DF</td><td>MF</td><td>13-bit fragment offset</td></tr>
<tr><td colspan="2">8-bit time to Live (TTL)</td><td>8-bit protocol</td><td colspan="4">16-bit header checksum</td></tr>
<tr><td colspan="7">32-bit source IP address</td></tr>
<tr><td colspan="7">32-bit destination IP address</td></tr>
<tr><td colspan="7">Options (if any)</td></tr>
<tr><td colspan="7">Data</td></tr>
</table>

Network Layer Issues

- **Long delay communication links**
  - IP needs no response and is completely unaffected by delay
  - IP is simply addresses on the front of your data
- **Intermittent communication links**
  - IP has no concept of a “session” to be interrupted
  - Each packet contains full address information
- **Data priority**
  - IP has a Type of Service field
  - Routers support priority queuing by transport protocol and port
  - Priority and Quality of Service options are being used and can be enabled
- **Overhead**
  - Lots of work on header compression due to Voice over IP and streaming video applications (RFC 2507, 2508 - 7 byte headers)
  - High volume data transfers use the largest packets possible

User Data Sizes (bytes)	100	500	1000	1400
IP (20)	16.6%	3.8%	1.9%	1.4%
UDP/IP (28)	21.8%	5.3%	2.7%	1.9%
TCP/IP (40)	28.5%	7.4%	3.8%	2.7%

IP Header Compression

- **The Voice over IP (VoIP) community is very interested in reducing the overhead of IP headers:**
  - IP/UDP/RTP header = 40 bytes (IP-20, UDP-8, RTP-12)
  - Voice samples = 20 bytes (G.729 default)
  - Over 2/3 of VoIP bandwidth would be used for protocol overhead
- **cRTP compresses 40 byte IP/UDP/RTP header to 2-4 bytes**
- **Wireless community also needs header compression (e.g. cell phone email, web browsing)**
- **RFC 2507 - IP Header Compression**

Abstract

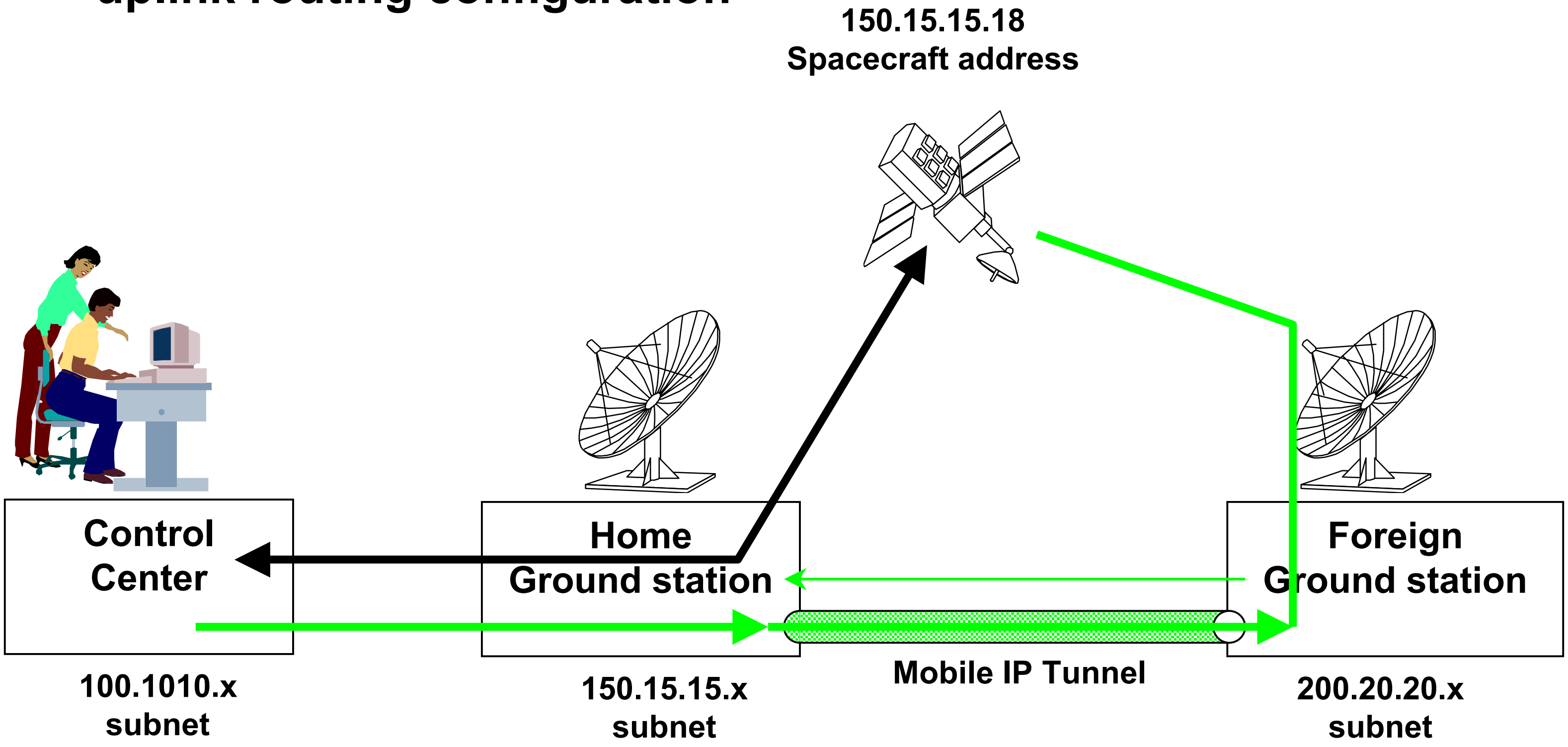
This document describes how to compress multiple IP headers and TCP and UDP headers per hop over point to point links. The methods can be applied to of IPv6 base and extension headers, IPv4 headers, TCP and UDP headers, and encapsulated IPv6 and IPv4 headers.

Headers of typical UDP or TCP packets can be compressed down to 4-7 octets including the 2 octet UDP or TCP checksum. This largely removes the negative impact of large IP headers and allows efficient use of bandwidth on low and medium speed links.

The compression algorithms are specifically designed to work well over links with nontrivial packet-loss rates. Several wireless and modem technologies result in such links.

Mobile IP Scenario

- Need to automatically determine which ground station to send commands through
- Downlink data is routed normally
- Mobile device registration with ground agents supports automatic uplink routing configuration

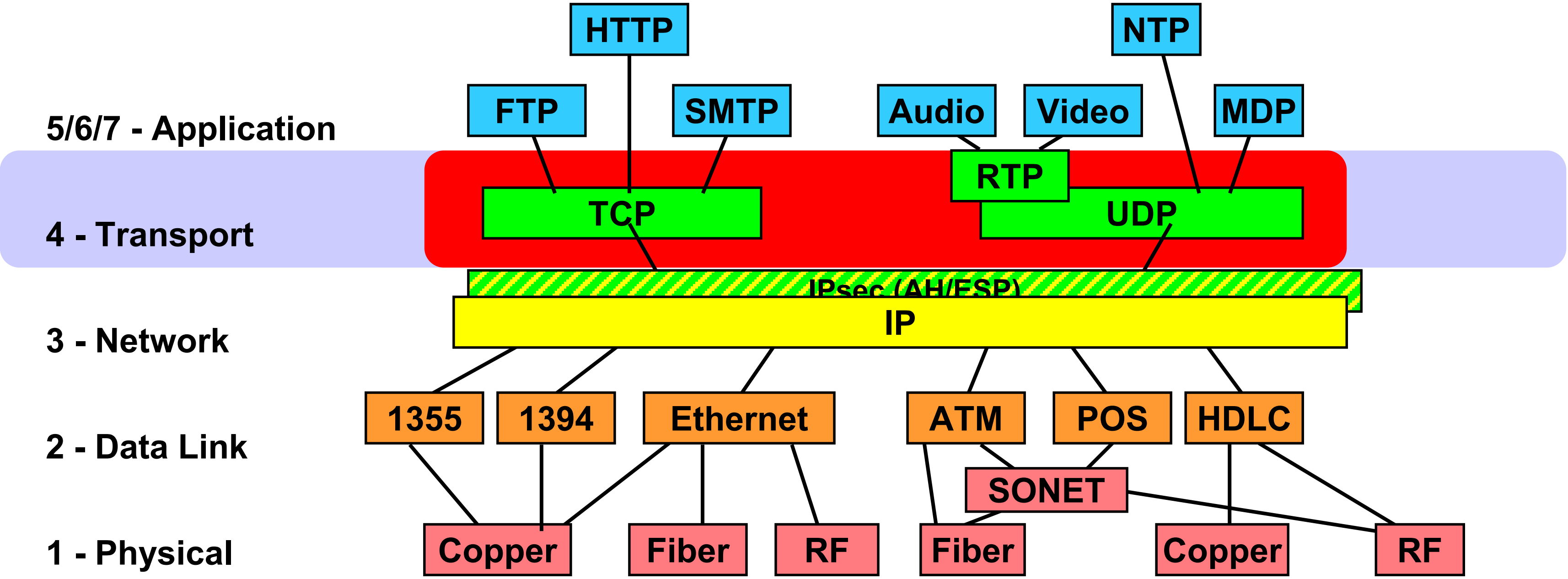


Security

- **Security for IP in space is not a new issue, it is just a continuation of existing security needed for space missions**
- **Security solutions can and should be deployed at multiple layers and locations**
  - RF - spread spectrum, frequency hopping, etc.
  - Link level encryption
  - IPsec options between network and transport layer
  - Application level encryption
- **Initial deployment of IP in space will probably use private networks just like the current ones that have been in use for the last 3 years**
- **Many security solutions are already widely available for use with IP and many more will be developed in the future**
- **Security solutions need to be tailored to an appropriate level for each mission based on - mission size, acceptable risk, mission budget, etc.**
- **Other groups within GSFC are working on security approaches.**

Transport Layer

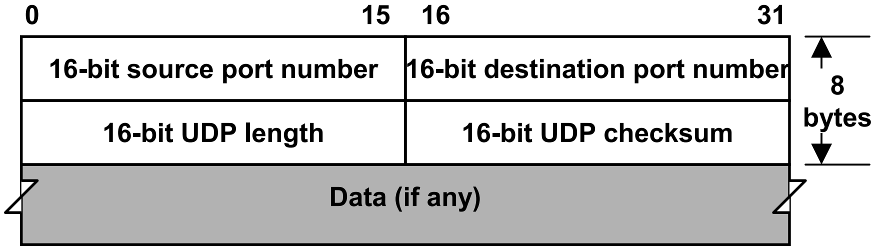
- **Common programming interface for applications (sockets)**
- **Primarily two delivery options**
  - TCP - “reliable” end-to-end data delivery
  - UDP - “send-and-forget” data delivery (similar to all current spacecraft frame delivery)
- **Implemented in end-system operating systems, “socket” API**



Transport Layer Protocols

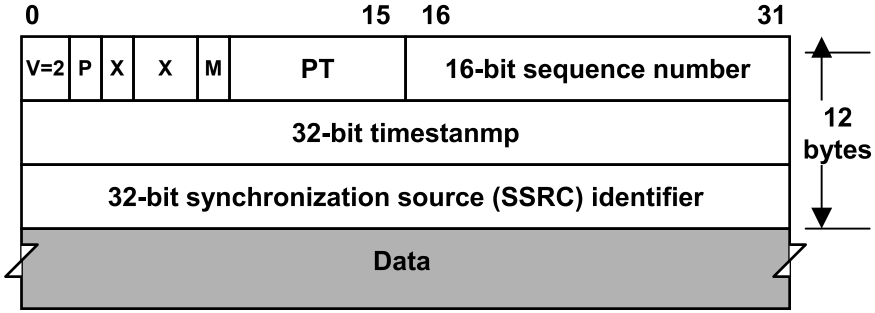
- **User Datagram Protocol (UDP)**
  - Simple header to multiplex user data over IP
  - No session setup or tear-down
  - Works on unidirectional links, unaffected by propagation delay
- **Feedback loop for reliable delivery is implemented by user**
- **Provides Internet interface that operates similar to traditional spacecraft communication systems**
- **Real-time Protocol (RTP) adds support for reconstructing real-time data streams over UDP**

UDP



0 15	16 31
16-bit source port number	16-bit destination port number
16-bit UDP length	16-bit UDP checksum
Data (if any)	

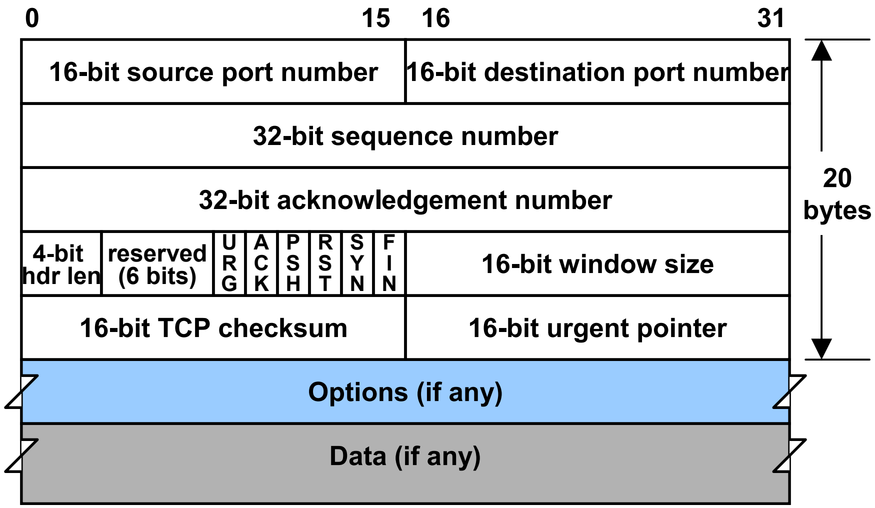
RTP



0					15	16 31
V=2	P	X	X	M	PT	16-bit sequence number
32-bit timestanmp						
32-bit synchronization source (SSRC) identifier						
Data						

Transport Layer Protocols

- **Transmission Control Protocol (TCP)**
  - Same multiplexing features as UDP
  - Additional fields to support “reliable” data delivery
  - Uses sequence numbered datagrams and acknowlegements
  - Also provides flow control in response to network performance
- **Sensitive to combination of data rate (bandwidth) and delay**
- **Sensitive to network errors and congestion**
- **Relatively tight feedback loop between end-systems**



0 15 16 31

16-bit source port number | 16-bit destination port number

32-bit sequence number

32-bit acknowledgement number

4-bit hdr len | reserved (6 bits) | URG | ACK | PSH | RST | SYN | FIN | 16-bit window size

16-bit TCP checksum | 16-bit urgent pointer

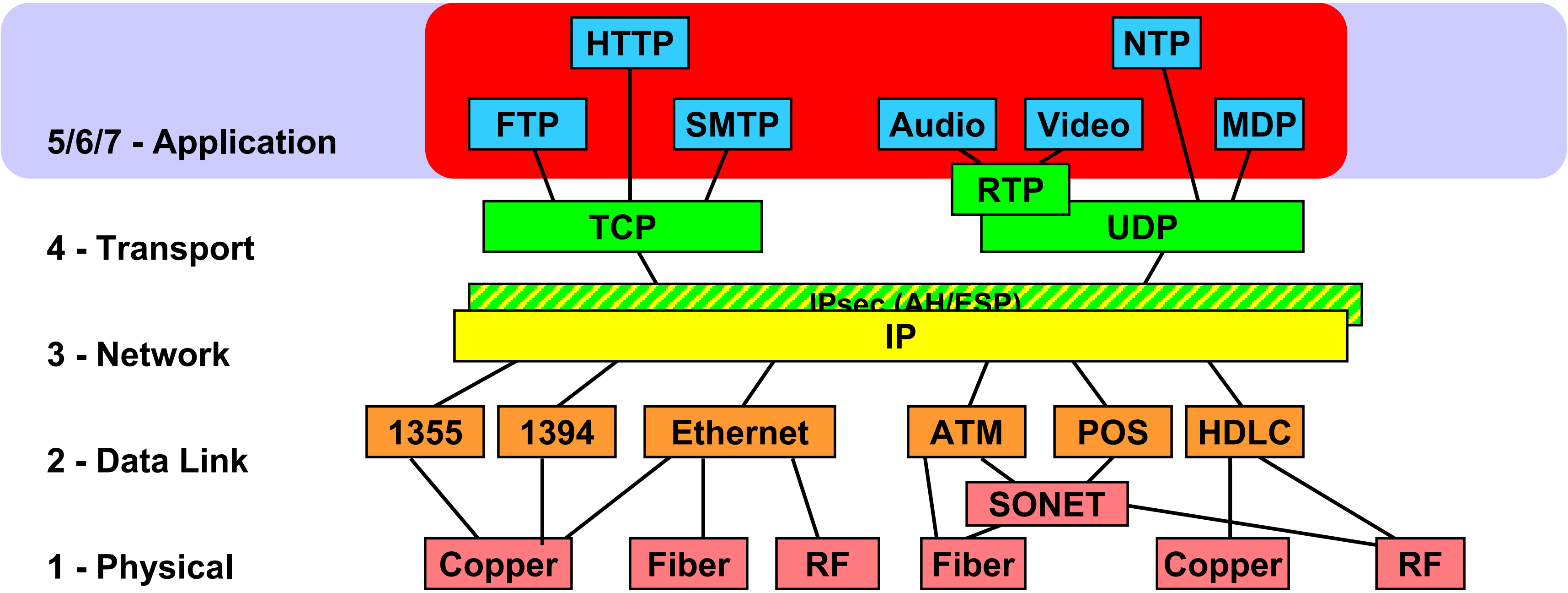
Options (if any)

Data (if any)

20 bytes

Application Layer

- Applications use the transport protocol best suited to their needs (e.g. UDP or TCP)
- Standard applications are available for file transfer, store-and-forward delivery, time synchronization, and non-data formats (audio, video)
- Users can develop their own applications to meet special needs



IP Operations Scenarios

- **Real time telemetry**
  - Unidirectional - UDP
  - Reliable - TCP

- **Reliably Downlink Recorded Science & Engineering Data**
  - Short Delay - FTP over TCP
  - Long Delay - MDP / PBP / MFTP / CFDP over UDP
  - Store & Forward - SMTP over TCP, MDP over UDP

- **Onboard Clock Synchronization**
  - Synchronization and clock drift mitigation - NTP

- **Commanding**
  - Store & Forward - SMTP or MDP
  - Reliable Realtime - TCP
  - Blind Realtime - UDP

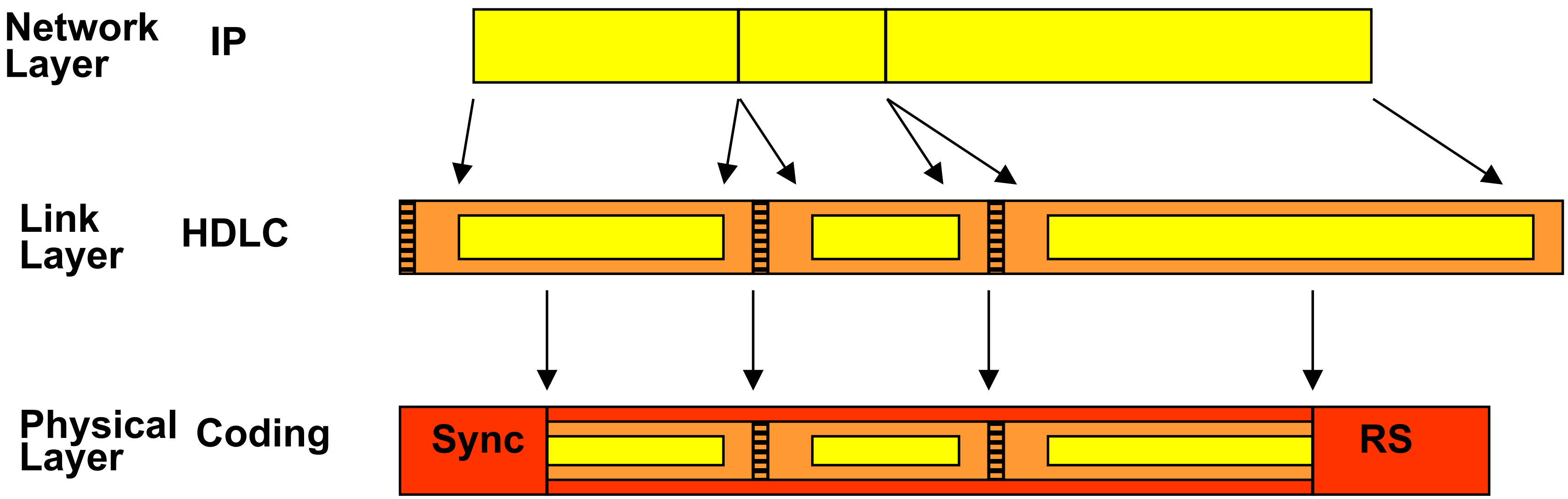
Multicast Dissemination Protocol

- **MDP - developed at Naval Research Lab, available on Solaris, Linux, Win32**
- **It's just an application so no operating system changes are needed**
- **Loose feedback loop required for mulitcast but also works good for space links with intermittent connectivity and/or long delay**
- **OMNI project testing this in lab and soon on UoSAT-12**
- **Basic MDP Protocol Features:**
  - Efficient one-to-many bulk data multicast dissemination
  - Use of selective negative acknowledgement (NACK) receiver-based protocol
  - Optional parity-based repair using forward error correction (FEC) coding techniques
  - Aggregation of control messaging for bandwidth efficiency
  - Good convergence in high error rate conditions
  - On-demand or timed dissemination of files or directories
  - Optional positive receipts from selected receivers
  - Support for EMCON (silent clients) modes of file transmission
  - Good properties for asymmetric and tactical operation
  - Tunable protocol parameters for adaptation to extreme network environments
- **Multi-hop store and forward can be added by embedding email addresses in header and using SMTP for final delivery**

Comparison - Internet & Current Space Protocols

- **Internet protocols provide significant addressing features and mass market usage not seen in current space protocols**
- **The primary strength of current “space” communication is the use of forward error correction, everything else is just data structures**
- **RF link (e.g. power, bandwidth, freq., coding) is “Space Unique”**
- **Internet community is addressing most of the protocol issues that were traditionally seen as “Space Unique”**
  - The rapidly growing mobile/wireless market needs space-like solutions
  - Voice over IP needs efficient data delivery
  - Network connectivity to automobiles creates a huge mobile constellation
- **NASA/Glenn Research Center and New Mexico State University are also comparing Internet and CCSDS protocols**

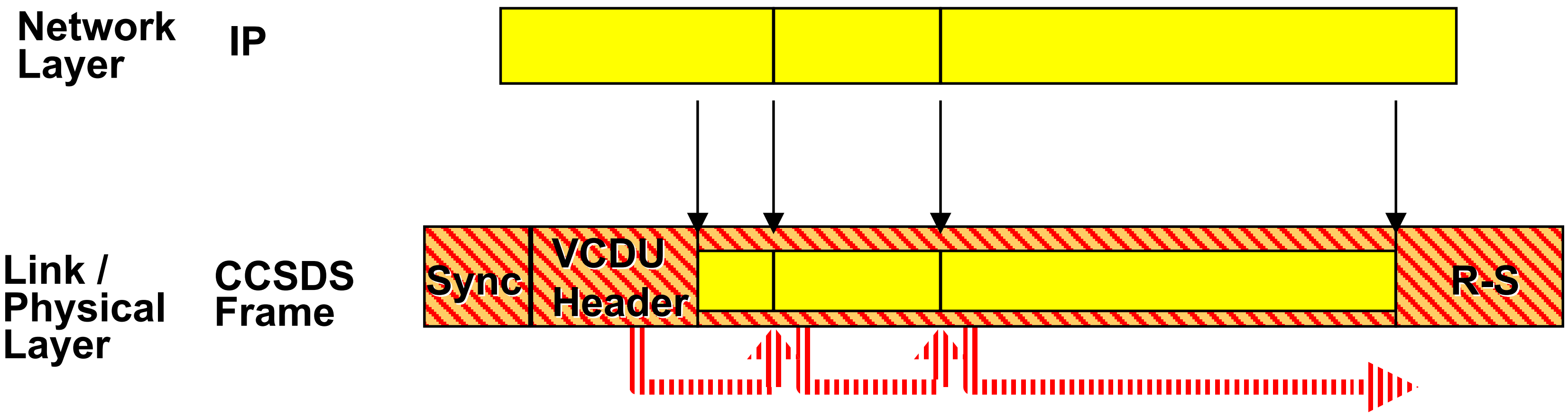
OMNI Space Link Framing of IP



- IP packets are variable length
- One HDLC frame per IP packet, with independent sync marks
- Coding at the physical layer provides a protected “bit-stream” service for the link layer. Physical layer requires no knowledge of link layer structure.

KEY: Network 🟨 Link 🟧 Physical 🟥

CCSDS Space Link Framing of IP



Network Layer **IP**

Link / Physical Layer **CCSDS Frame**

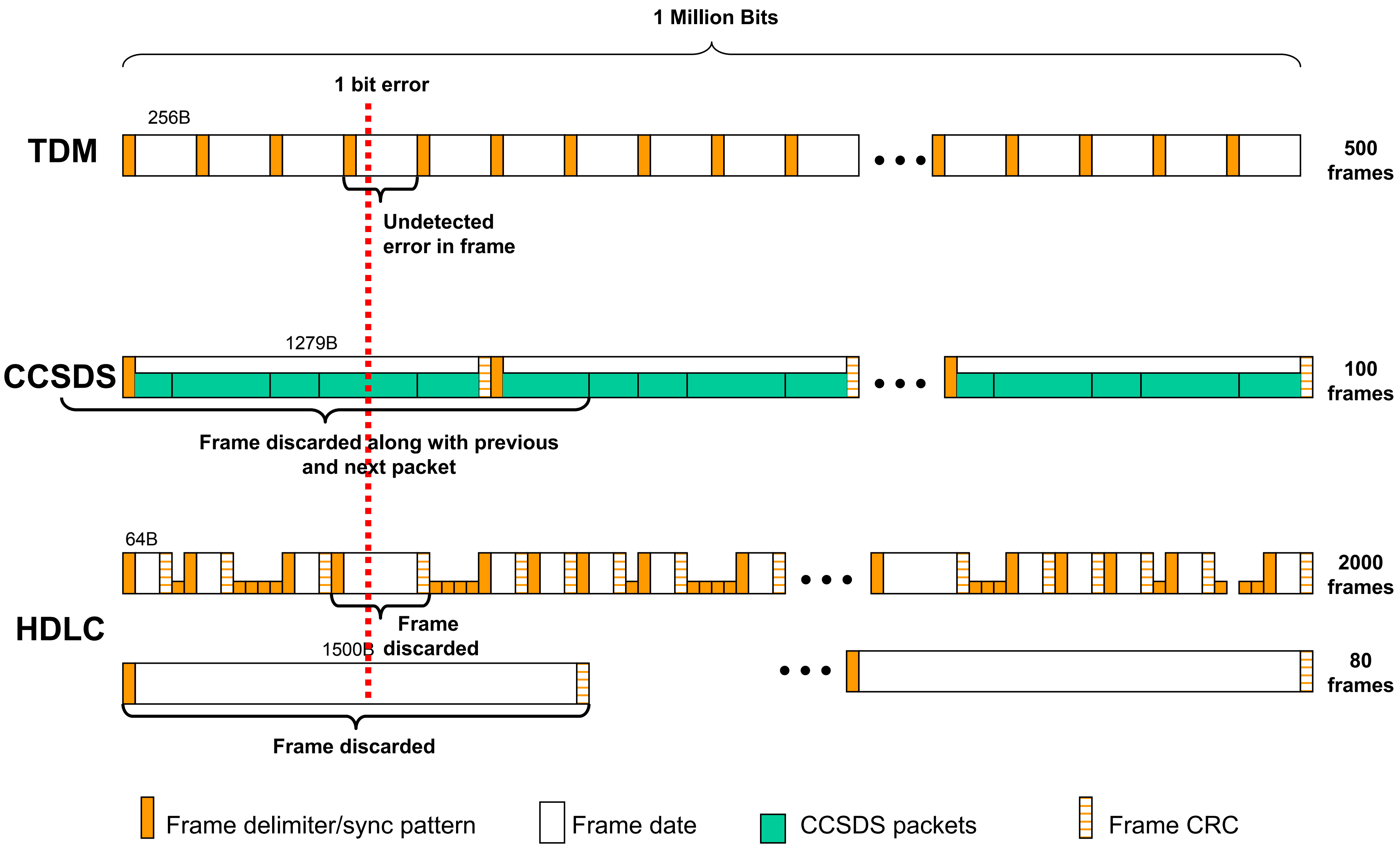
Sync | VCDU Header | R-S

- **IP packets are variable length**
- **CCSDS frames are fixed length, combining Link Layer framing and Physical Layer coding.**
- **IP packets become segmented as they are blocked into fixed sized frames.**
- **Lack of a distinct Link layer with an independent sync mark means that the Link/Physical layer must have knowledge of the internal structure of the network layer in order to extract it.**

KEY: **Network** 🟨 **Link** 🟧 **Physical** 🟥

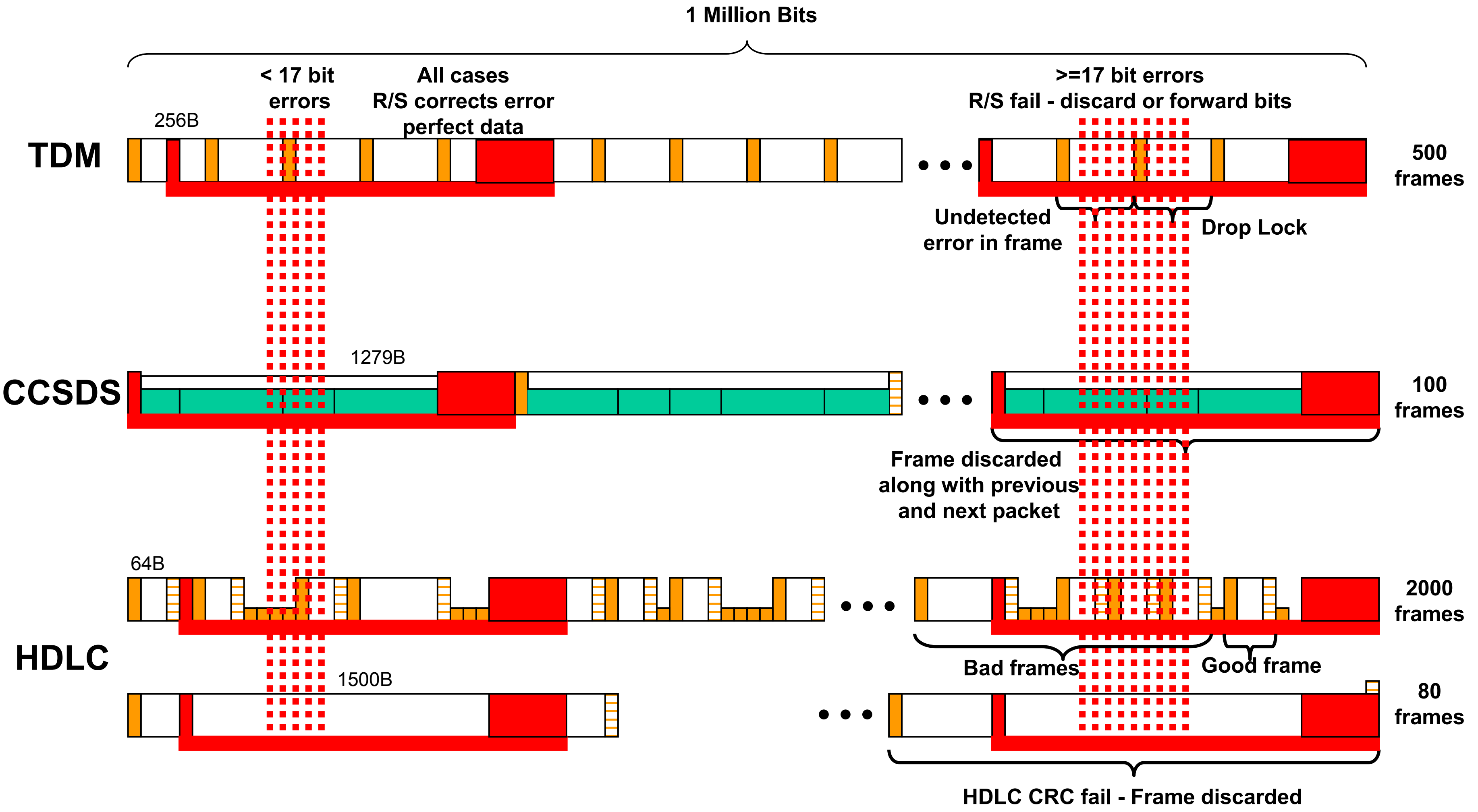
Frame Comparison (no R/S) - BER 10^{-6}

Average 1 bit in error in 1 million bits - All other bits perfect



Frame Comparison (with R/S) - BER 10^{-6}

Average 1 bit in error in 1 million - with R/S either perfect or very bad

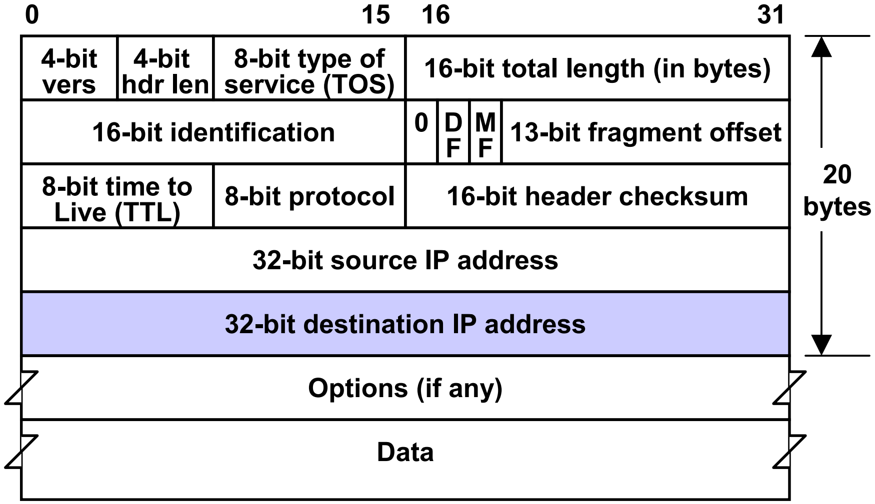


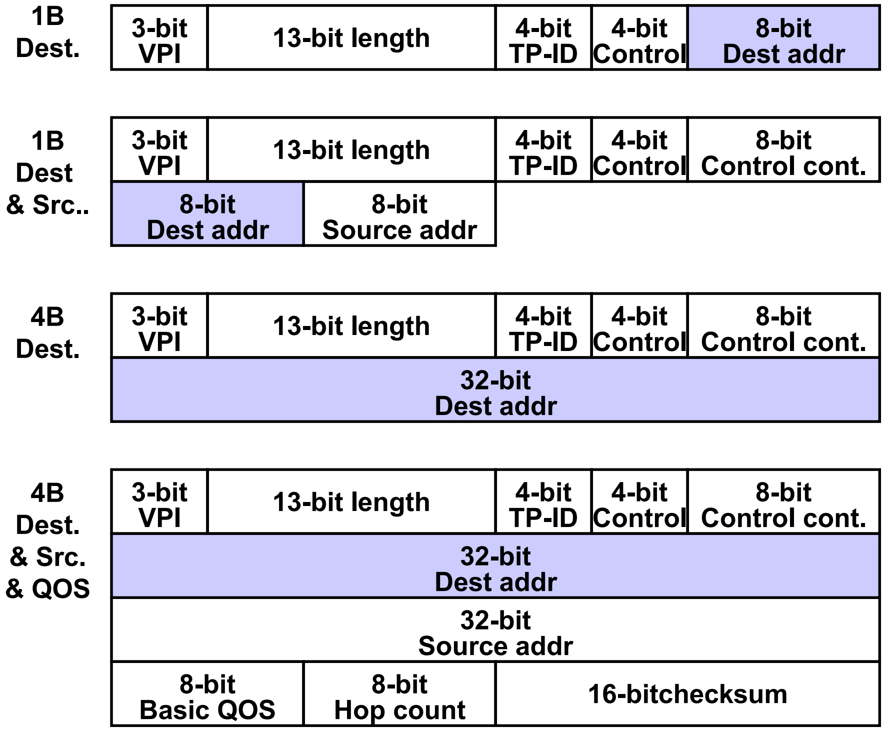
🟧 Frame delimiter/sync pattern ☐ Frame date 🟥 R/S coding 🟩 CCSDS packets ▤ Frame CRC

IP & SCPS-NP Comparison

- IPv4 - fixed 20 byte header
- Options after fixed header
- Automated routing protocols
- Built into all operating systems

- SCPS-NP - variable header 4-20 bytes
- Options throughout header
- Requires managed configuration
- Not supported by OS vendors
- Drops features to reduce overhead





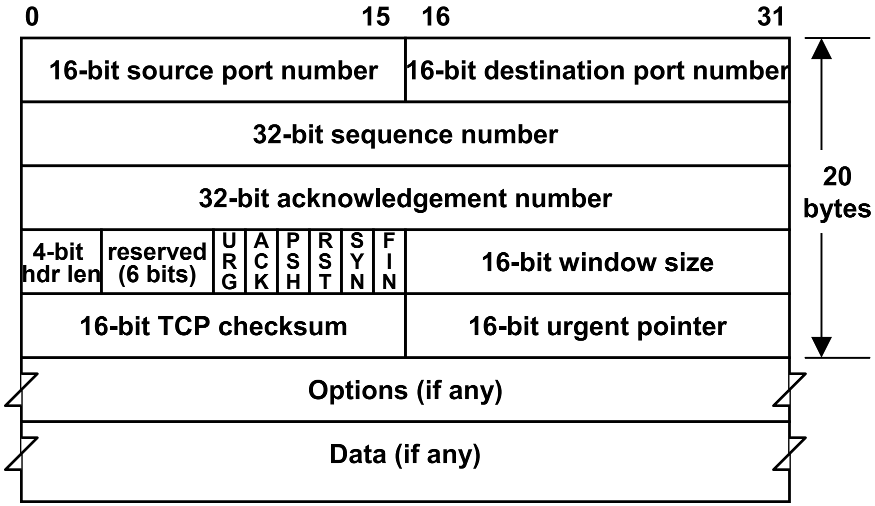
IPsec & SCPS-SP Comparison

- IPsec - variable headers
- Lots of options
- Lots of commercial implementations
- Automated support tools
- Used by thousands (e.g. banks, corporations, .coms) for critical applications

- SCPS-SP - variable headers
- Lots of options
- Few implementations
- Minimal automated support tools
- No known usage

TCP & SCPS-TP Comparison

- **TCP - fixed 20 byte header**
- **Options after fixed header**
- **Retransmit and flow control logic**
- **Built into all operating systems**
- **Applications rely on reliable delivery or connection failure indication**



16-bit source port number | 16-bit destination port number

32-bit sequence number

32-bit acknowledgement number

4-bit hdr len | reserved (6 bits) | URG | ACK | PSH | RST | SYN | FIN | 16-bit window size

16-bit TCP checksum | 16-bit urgent pointer

Options (if any)

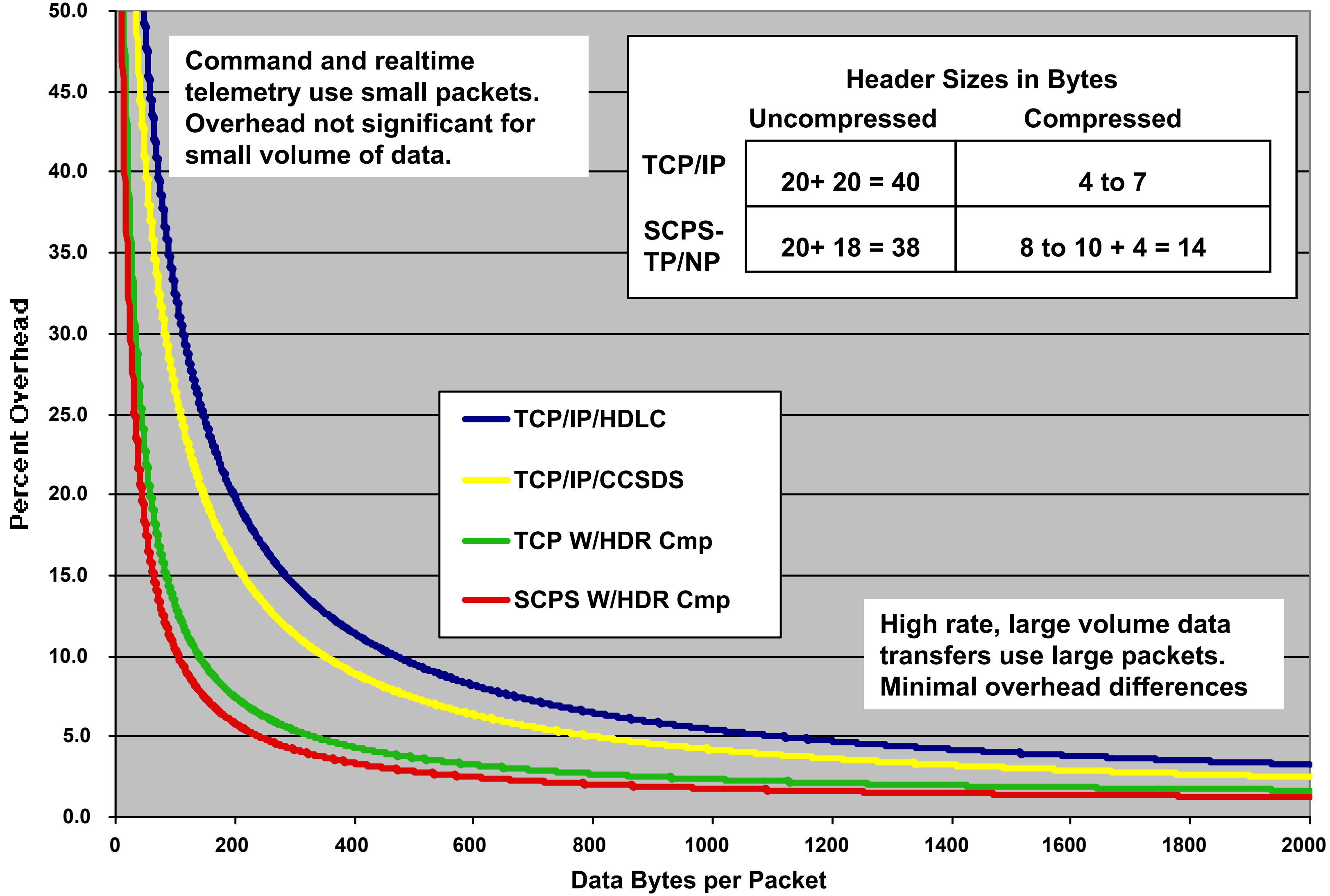
Data (if any)

- **SCPS-TP - standard TCP header**
- **SCPS-TP options in TCP option space**
- **Modified TCP control logic**
- **Not supported by OS vendors**
- **Best effort mode**
  - –If application trusts TCP reliable delivery, errors break application logic
  - –If application handles reliable and unreliable modes, could use UDP and avoid TCP session setup and teardown
- **Compressed SCPS-TP header**
  - –Variable lengths
  - –Compression by dropping features

8-bit Connect ID	8-bit Comp. Hdr bit vector	16-bitchecksum

8-bit Connect ID	8-bit Comp. Hdr bit vector	32-bit sequence --->
<----- number		16-bitchecksum

Bit-Efficiency Comparison



Command and realtime telemetry use small packets. Overhead not significant for small volume of data.

Header Sizes in Bytes

	Uncompressed	Compressed
TCP/IP	20+ 20 = 40	4 to 7
SCPS-TP/NP	20+ 18 = 38	8 to 10 + 4 = 14

High rate, large volume data transfers use large packets. Minimal overhead differences

Reliable File Transfer Comparison

- **Internet uses reliable file transfer applications built on both TCP and UDP**
- **TCP**
  - FTP
  - NFS
  - HTTP
- **UDP**
  - NFS
  - MDP
  - MFTP
- **MDP application level store&fwd, add third party easily**
- **These all readily available**

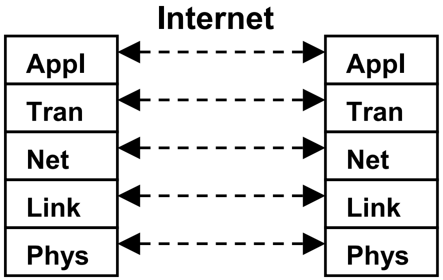
- **CCSDS is developing reliable file transfer applications built on SCPS-TP and UDP**
- **SCPS-TP**
  - SCPS-FP
  - CFDP
- **UDP or CCSDS packets**
  - CFDP
- **CFDP application level store & fwd through third party**
- **Being developed**

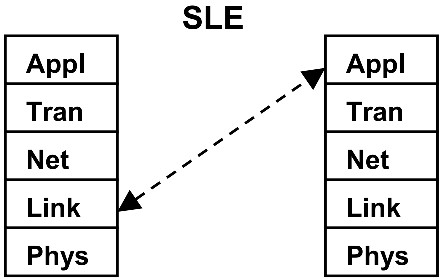
Internet & SLE Comparison

CCSDS Space Link Extension (SLE) concept is difficult to relate to Internet protocols. It encompasses both data delivery and remote management and is based on Internet concepts like CORBA and remote objects.

- **Internet layering focuses on delivering data between users and hiding the lower layer framing details.**
- **Remote access LAN/WAN analyzers can return frames for diagnostic purposes.**
- **Internet has lots of remote monitoring and management protocols and packages**

- **SLE concept focuses on delivering space link data frames and packets to users for further processing**
- **SLE contains data delivery and network management functions**
- **SLE requires gateways between space link and ground network**





Standards Bodies

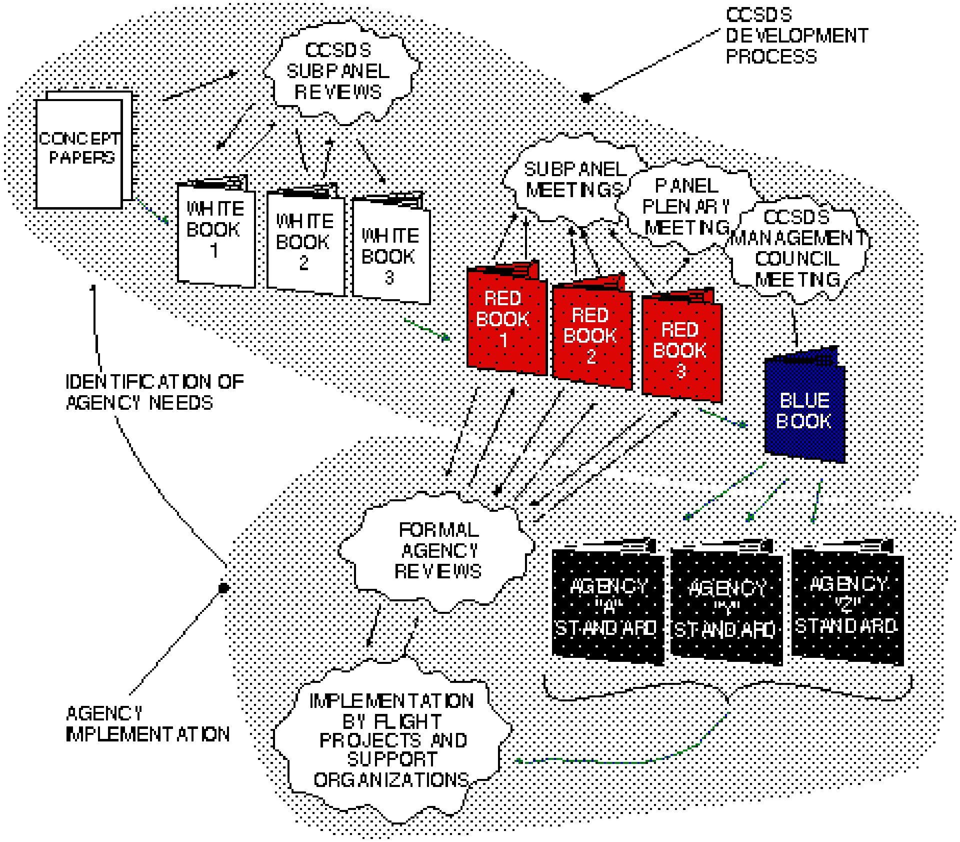
- **What is the IETF**
  - International communication/networking companies, huge resources, commercial drivers
  - Standards are based on interoperable implementations and commercial deployment
  - Specifications are very strict with limited options
  - Rapid development and deployment to respond to evolving Internet
  - Product life-cycle of 2-3 years

- **What is CCSDS**
  - International space agencies, limited resources, limited commercial support
  - CCSDS develops engineering concept documents, users work out implementation
  - Recommendations require international agreement resulting in options to satisfy all parties
  - Process very similar to ISO which developed GOSIP
  - Development and deployment not driven by market pressures

IETF and CCSDS Processes

- **IETF RFC 2026 - Internet Standards Process:**
  - "In general, an Internet Standard is a specification that is ***stable and well-understood, is technically competent, has multiple, independent, and interoperable implementations with substantial operational experience, enjoys significant public support,*** and is recognizably useful in some or all parts of the Internet."

- **CCSDS NASA Center Document Review Process:**
  - "The NASA review of the subject document will be based upon the reviews performed by the affected NASA Centers; you are requested to coordinate such a review at your Center. ***If no RIDs are received by the due date, it will be assumed that your Center has no objection to NASA's approving the document.*** "



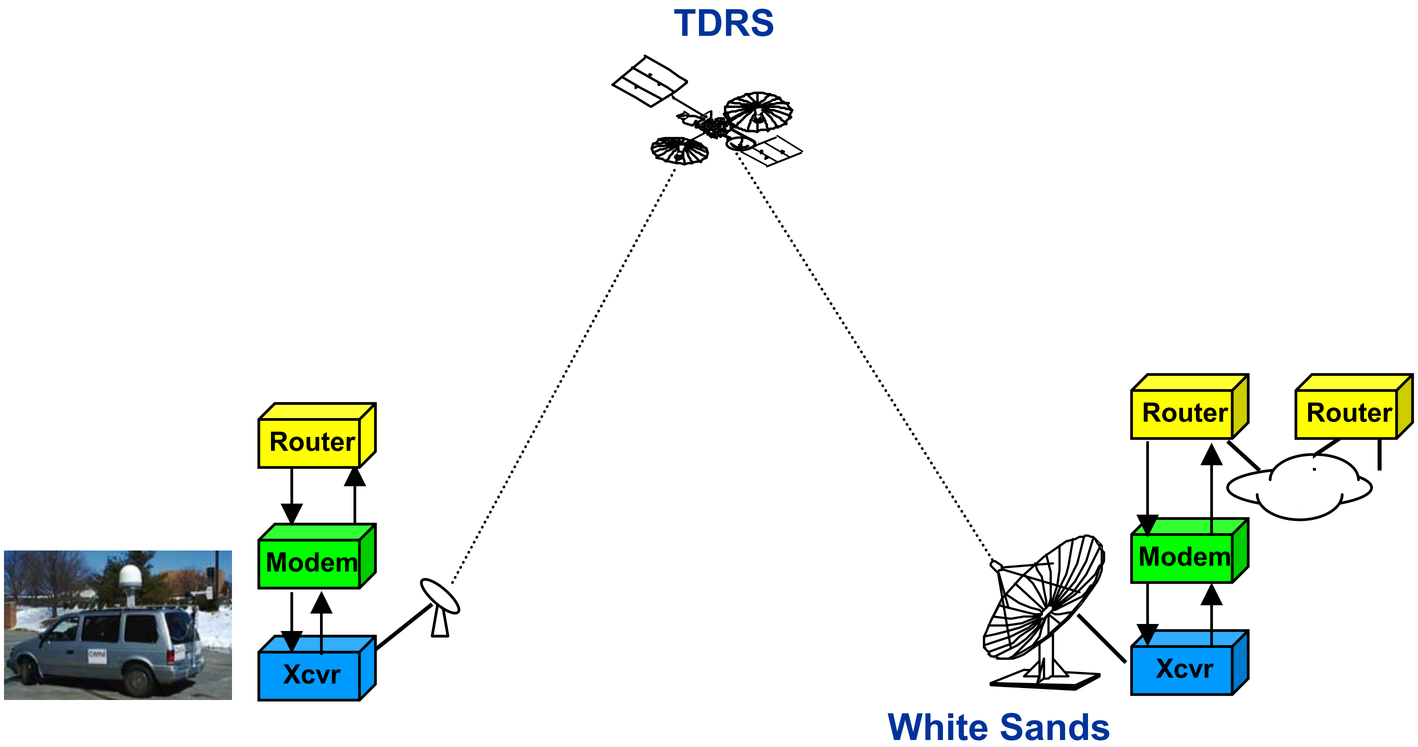
Technical Summary

- **The main feature of today's "space" protocols is forward error correction, everything else is data structures**
- **Once coding cleans up the physical link, any framing can be used**
- **HDLC over Reed-Solomon or other coding is not a problem once the interface is defined as a bit level interface**
- **A clean interface between the RF and link layer allows modular upgrades using faster and faster COTS network equipment**
- **HDLC, IP, UDP are completely unaffected by delay and intermittent connections**
- **Internet and commercial resources provide future products if NASA uses IP technology**

Standard Internet protocols work in space as well as other "space" protocols - some additional bit overhead which is offset by significant benefits

Operating Missions as Nodes on the Internet (OMNI)

Experimental Results - TDRSS



Ron Parise - Computer Sciences Corp

Ron.Parise@gsfc.nasa.gov
(301) 286-3896

Experimental Results

- **OMNI project has used existing antennas, transmitters, receivers, convolutional coders/decoders to demonstrate Internet protocols in space**

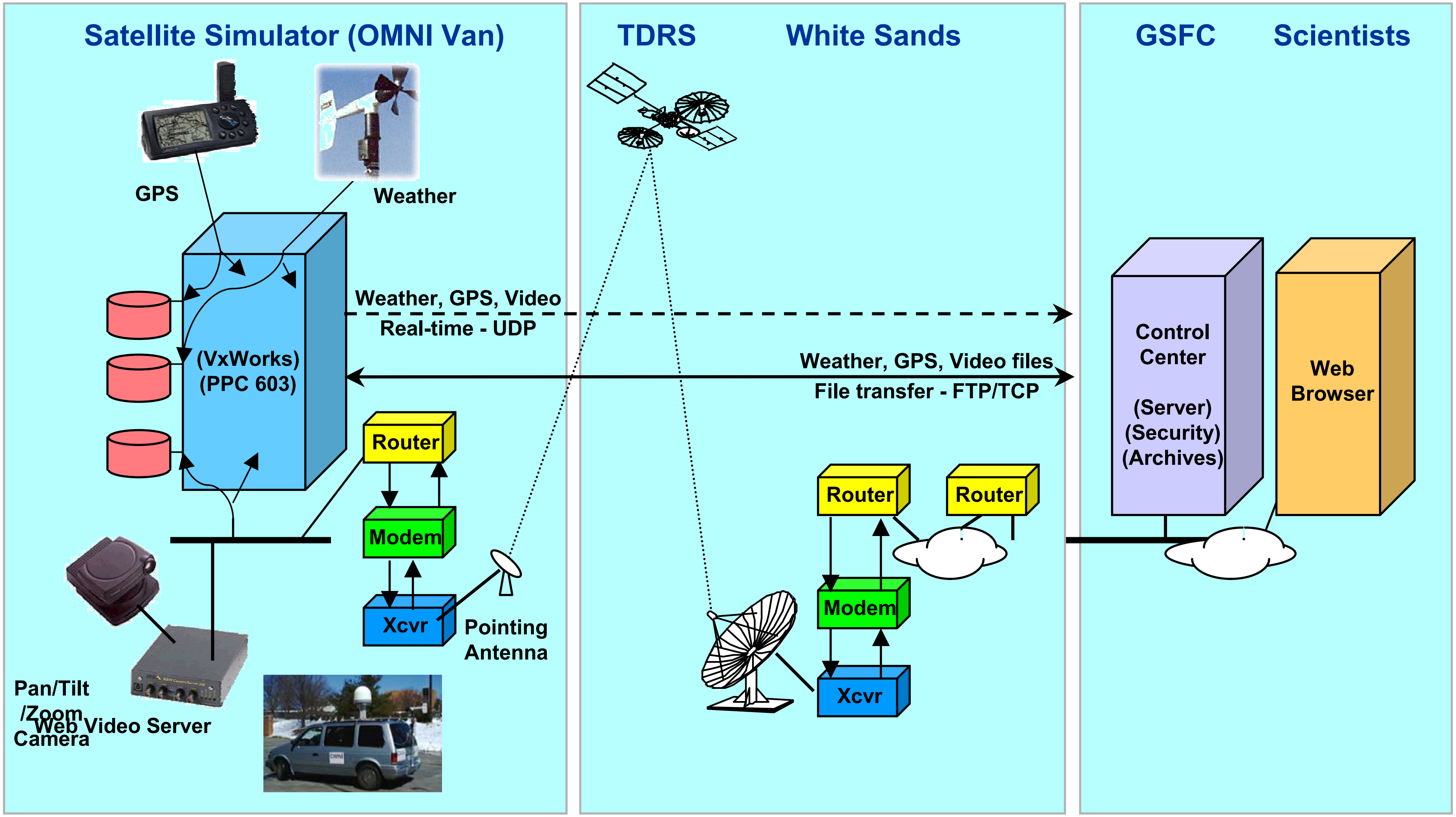
- **TDRSS tests**
  - OMNI van
  - Black Sea Solar Eclipse
  - Inspection Day 99

- **Demonstrated a wide range of data delivery options using many protocols**
  - Realtime telemetry over a one-way link
  - Interactive commanding
  - Stored data delivery
  - Telemetry
  - Images
  - Audio
  - Etc.

Demonstrating Internet in Space

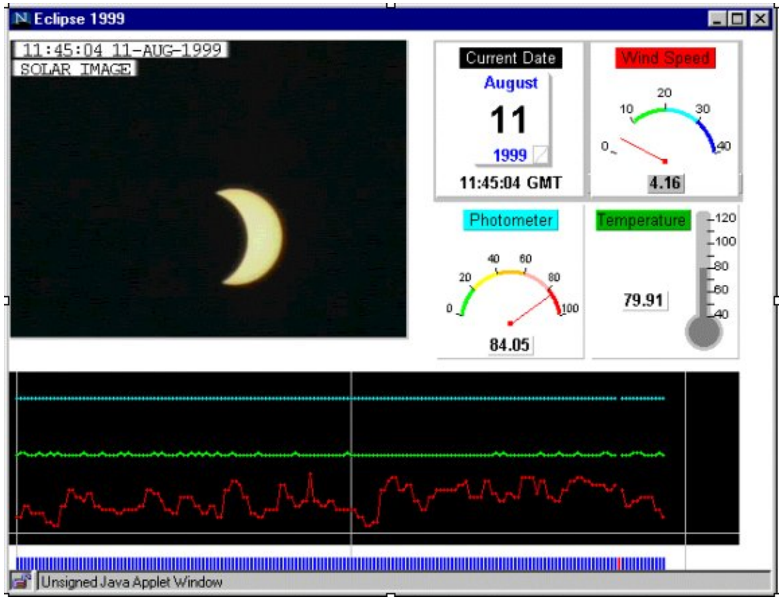
- Designed and built OMNI prototype
- Over 25 demos (> 300 people) (1-4/99)

TDRSS Satellite Demonstration System



Total Solar Eclipse Webcast Live From the Black Sea

- Live images, GPS, and weather data
- E-mail to ship
- Web browsing from ship
- Voice over Internet
- Realvideo—audio/video multicast



11:45:04 11-AUG-1999

SOLAR IMAGE

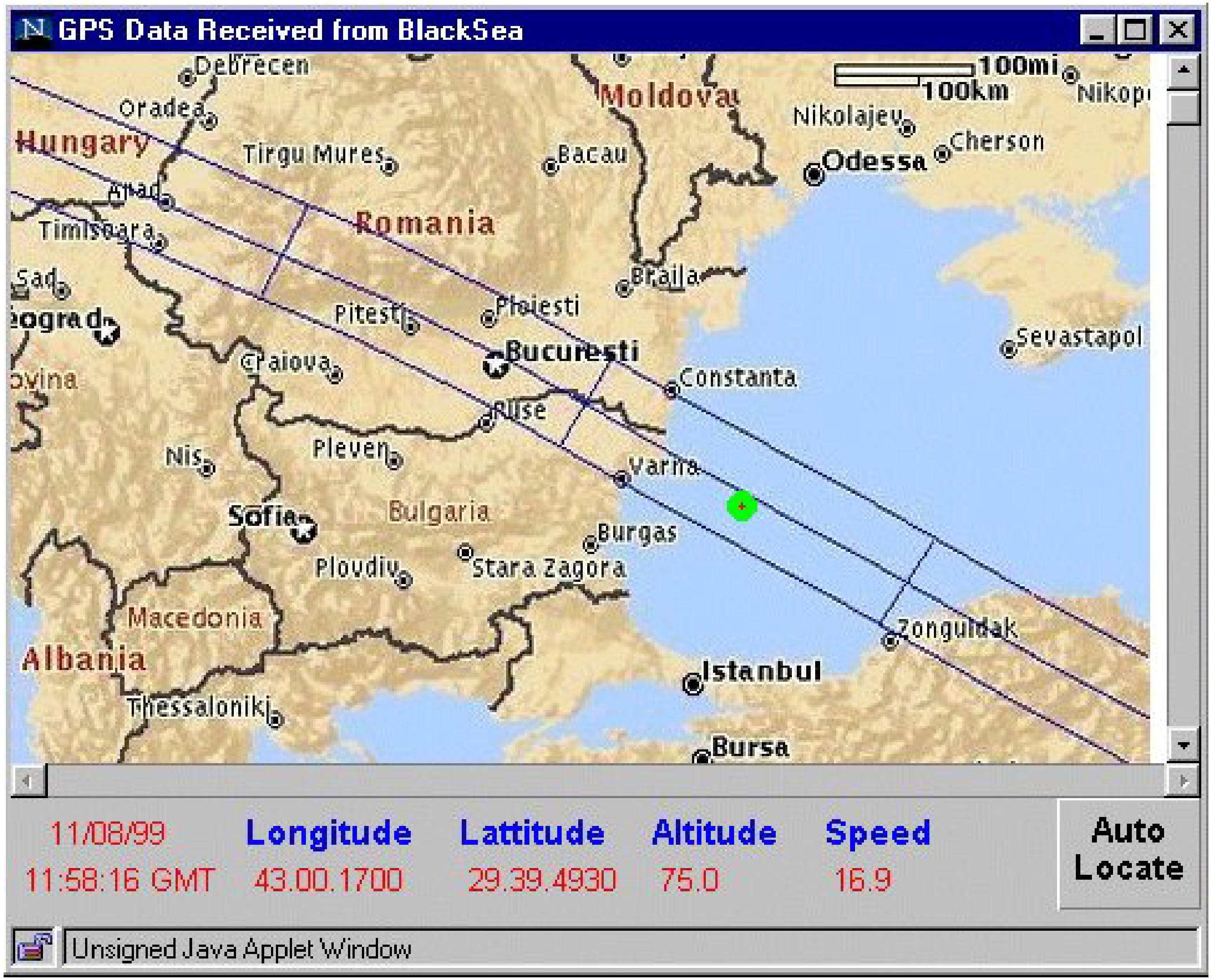
Current Date
August
11
1999
11:45:04 GMT

Wind Speed
4.16

Photometer
84.05

Temperature
79.91

GPS Data Display Applet



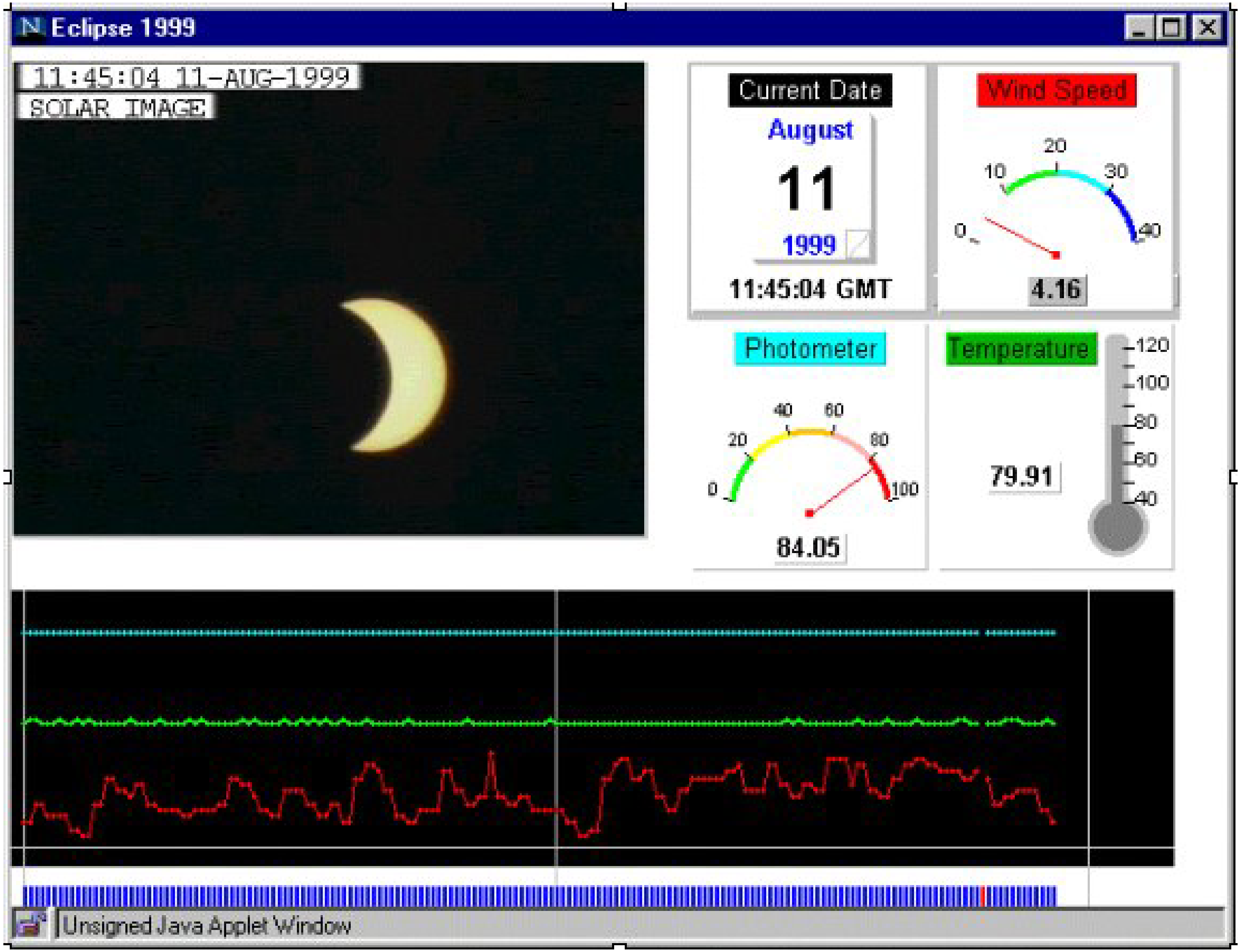
GPS Data Received from BlackSea

11/08/99	Longitude	Lattitude	Altitude	Speed
11:58:16 GMT	43.00.1700	29.39.4930	75.0	16.9

Auto Locate

Unsigned Java Applet Window

Eclipse Display Applet



Early Morning Eclipse Excitement

- Outreach to museums and public
- Thousands of simultaneous accesses (>10 million hits over 12 hours)
- Over 10,000 eclipse movie downloads

Black Sea

MD Science Center

GSFC

OMNI Van Applications

- **OMNI weather, GPS, images**
  - Real-time data sent by UDP/IP
  - Playback data sent by FTP/TCP/IP
- **Blind commanding using UDP/IP**
- **HTTP access to camera server for configuration and commanding**
- **Telnet from Lab to the prototype spacecraft**
  - Upload and run new software
  - Reliable commanding
- **NFS file transfer from prototype spacecraft**
- **FTP transfer starting on one TDRSS link and finishing on another**
- **Secure VPN link from OMNI Van to Lab**
- **TDRSS links using 2-way SSA, 2-way MA, and return-only MA**

Eclipse 99 Applications

- OMNI weather, GPS, images
- Web browser on ship used to check weather forecasts and the OMNI web site
- Internet Phone used for Voice over IP audio conversations between GSFC and the ship
- AOL Instant Messenger from ship to participating museums
- Email from ship to anywhere
- Telnet from ship to anywhere
- RealVideo from ship to Ames for streaming video

Inspection Day ‘99 Applications

- OMNI weather, GPS, images
- Audio/Video Tours of Goddard
- Downloaded demo copy of Iphone using web browser in van via TDRSS
- Internet Phone used for Voice over IP audio conversations between GSFC and JSC
- Email from van to anywhere
- Telnet from van to OMNI web server to edit web pages
- RealVideo from van to GSFC for streaming video

TDRSS Tests Summary

- Internet Protocols work over a geosynchronous link
- UDP/IP works for return-only one-way links which are identical to those used by current spacecraft
- All the Internet protocols operated over the same RF links as current TDM and CCSDS protocols
- OMNI tested a wide variety of UDP/IP and TCP/IP applications with no additional TDRSS/WSC modifications needed
- Our systems were implemented with standard COTS network equipment and software

http://ipinspace.gsfc.nasa.gov/

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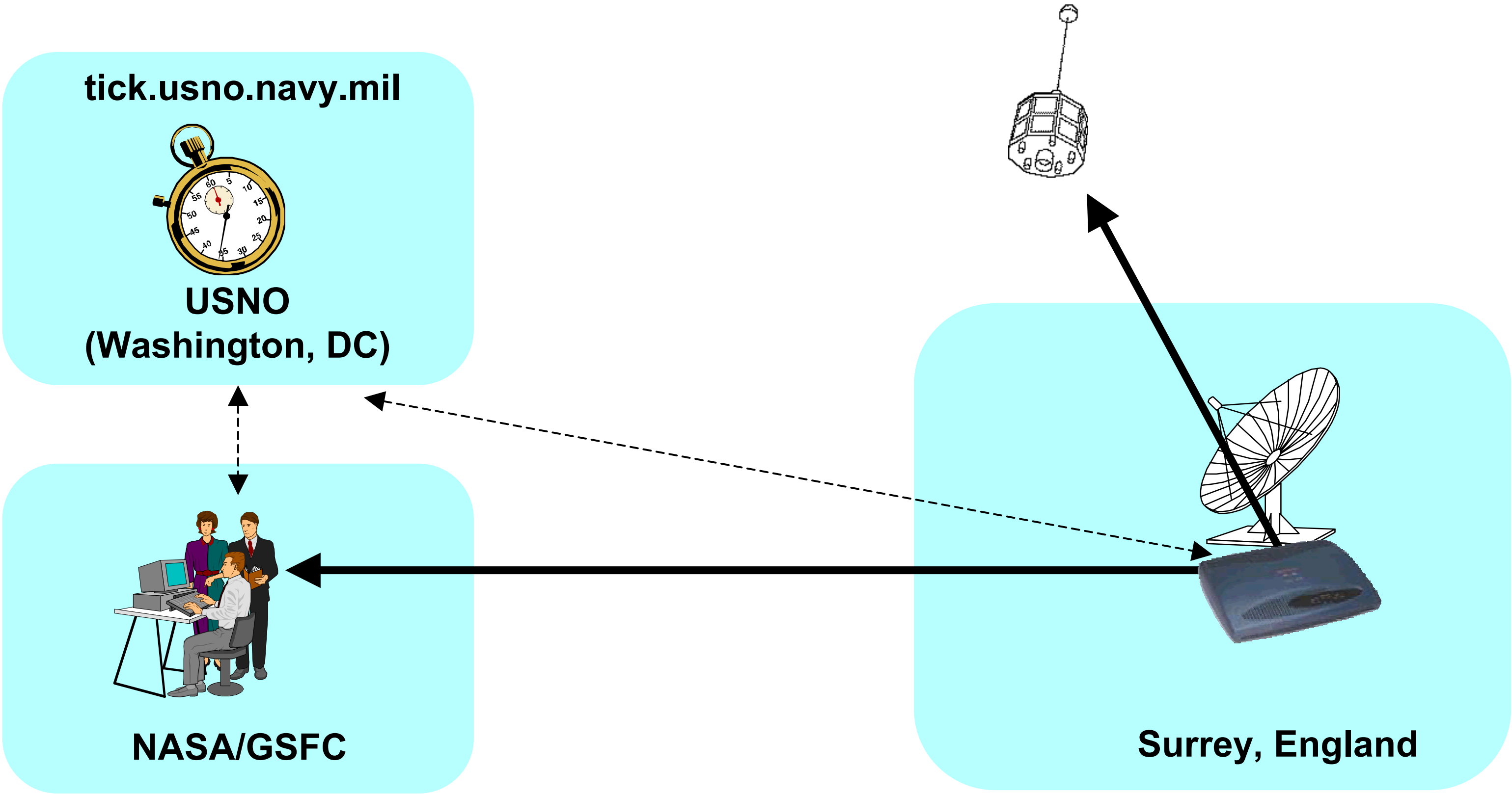
Operating Missions as Nodes on the Internet (OMNI)

Experimental Results - UoSAT-12



tick.usno.navy.mil

USNO
(Washington, DC)

NASA/GSFC

Surrey, England

Ed Criscuolo - Computer Sciences Corp

Ed.Criscuolo@gsfc.nasa.gov
(301) 794-4072

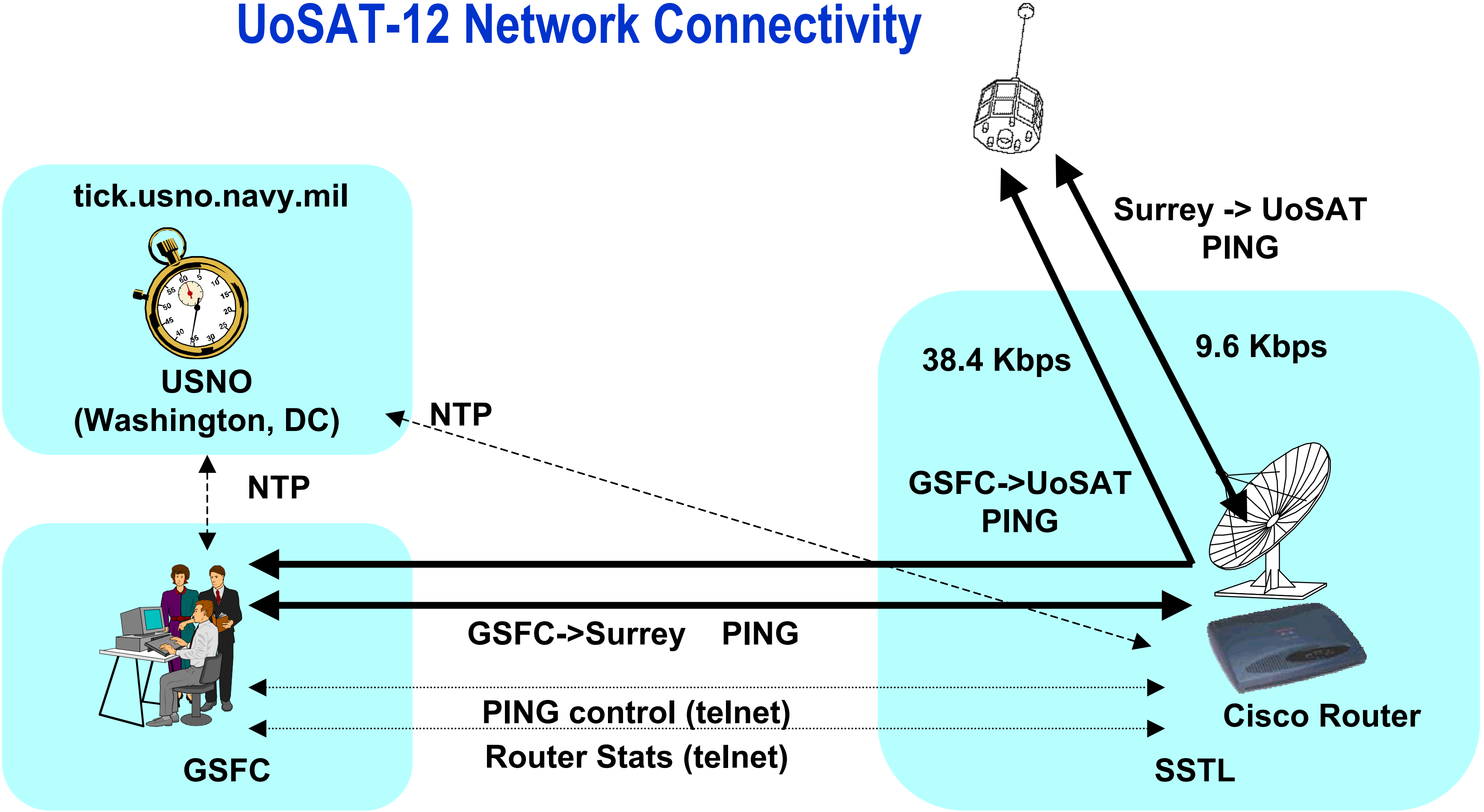
Next Up—An On-Orbit Flight Test!

UoSAT-12 Flight Tests

- **Idea in Nov. 1999 (Thankgiving)**
- **Contract in place Feb. 2000**
- **Operational code on spacecraft, ground system modified, data flowing April 2000**
- **Basic Connectivity Tests (PING) - Apr. 10, 2000**
  - Test operation of IP over HDLC on UoSAT-12
- **Automated Spacecraft Clock Sync (NTP) - Apr. 14, 2000**
  - End-to-end connectivity (UoSAT-12 to Naval Observatory)
  - Validation of NTP operation in space
- **Reliable File Transfer (FTP) - June 7, 2000**
  - Test FTP/TCP operation over UoSAT-12 space link
  - Adjust TCP parameters for limitations of UoSAT-12
- **Realtime Telemetry (UDP) - Nov - Dec 2000**
  - Rapid deployment (4 days) of Stanford receive-only ground station for UoSAT-12 support during Space Internet Workshop
- **Web Browser Access (HTTP) - Jan. 25, 2001**
  - Retrieve data and monitor status using standard web browser

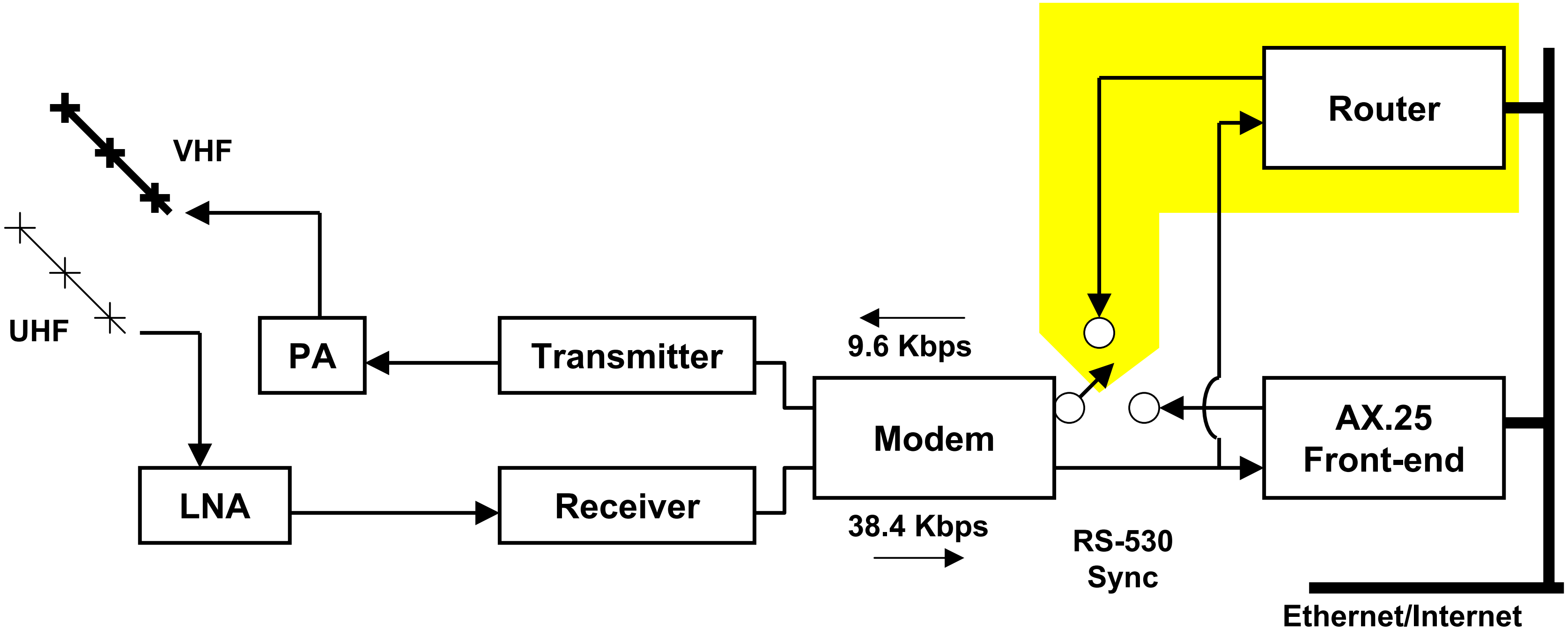
World's First Spacecraft on the Internet

UoSAT-12 Network Connectivity



Surrey Ground Station Modifications

- **Surrey Ground Station (SSTL)**
  - Installed Cisco router with RS-530 interface at SSTL
  - Interfaced router to clock/data from SSTL transceiver
  - Verified router receiving HDLC frames
  - Uploaded new SCOS modules to secondary CPU onboard UoSAT-12



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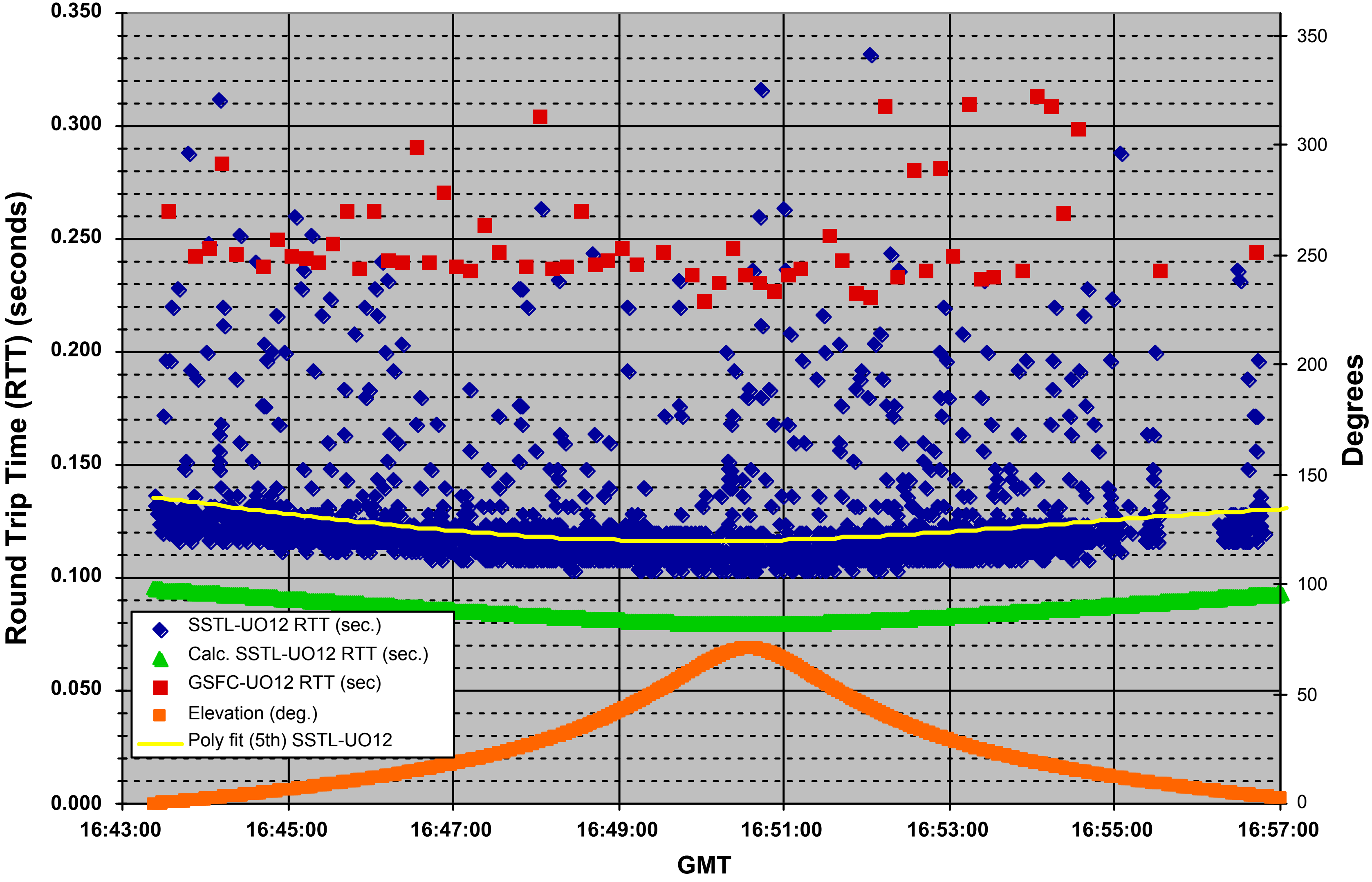
PING Test—April 10, 2000



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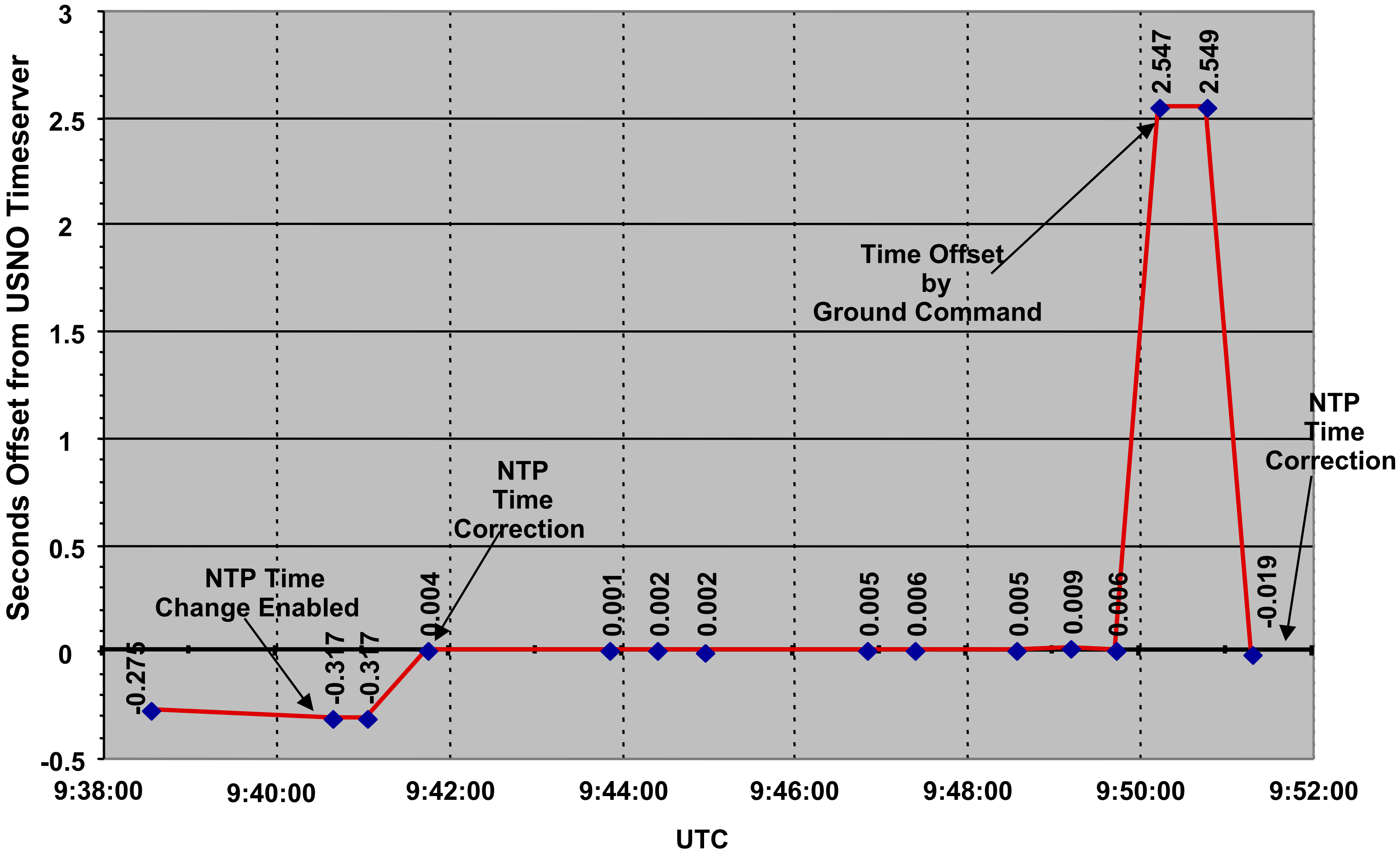
NTP Test 1—April 14, 2000



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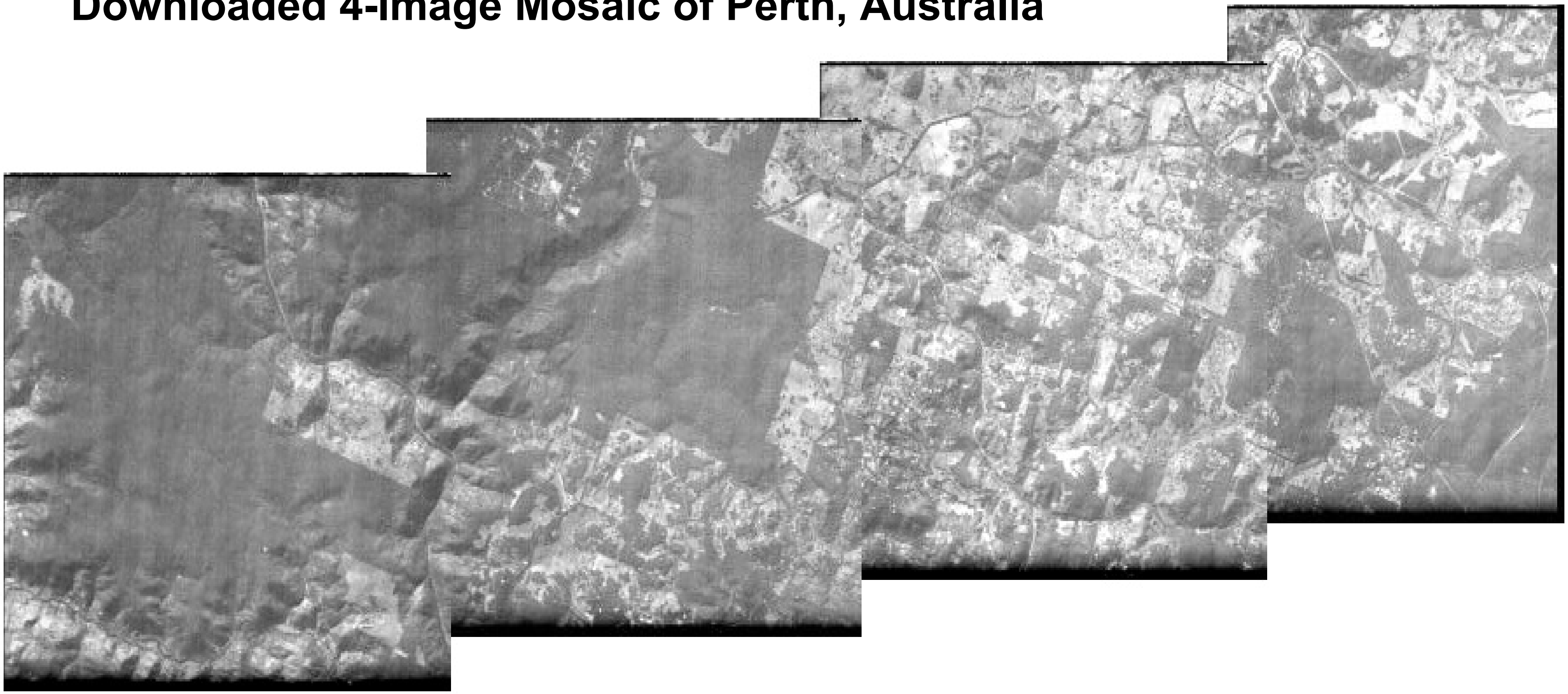
FTP Test 3—June 7, 2000

Downloaded 4-Image Mosaic of Perth, Australia



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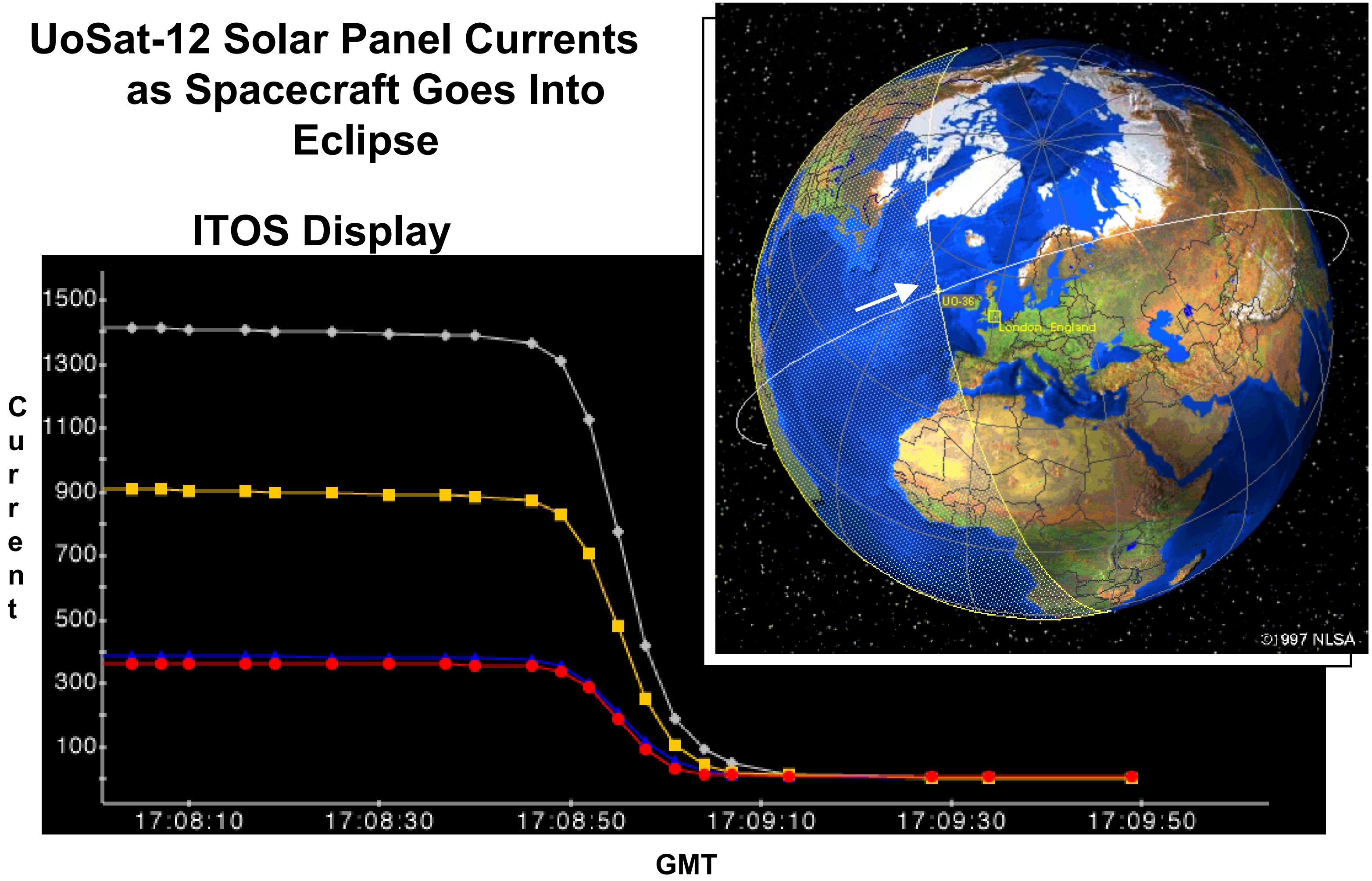
UDP Telemetry—December 13, 2000

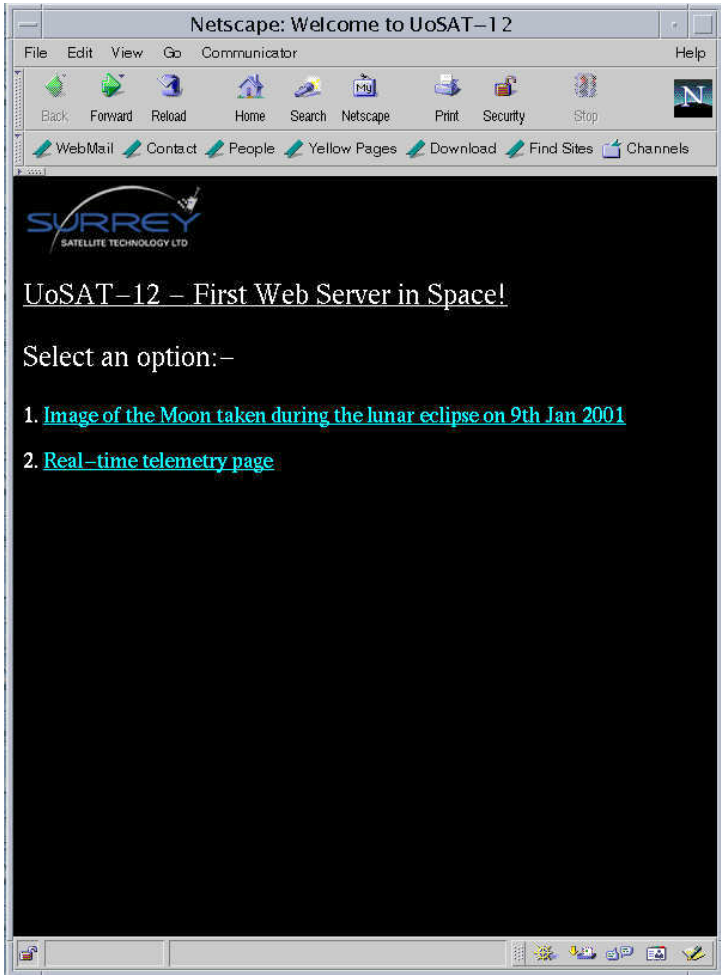
UoSat-12 Solar Panel Currents as Spacecraft Goes Into Eclipse

ITOS Display



World’s First Spacecraft on the Internet

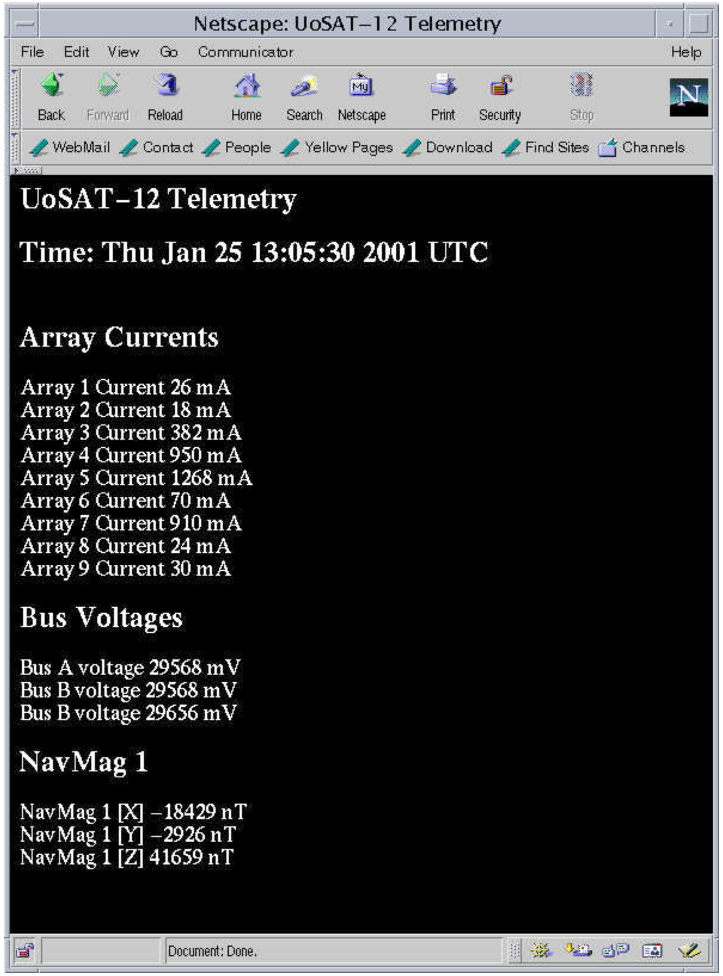
HTTP Telemetry Test—January 25, 2001



UoSAT–12 – First Web Server in Space!

Select an option:–

1. Image of the Moon taken during the lunar eclipse on 9th Jan 2001
2. Real–time telemetry page



UoSAT–12 Telemetry

Time: Thu Jan 25 13:05:30 2001 UTC

Array Currents

Array 1 Current 26 mA
Array 2 Current 18 mA
Array 3 Current 382 mA
Array 4 Current 950 mA
Array 5 Current 1268 mA
Array 6 Current 70 mA
Array 7 Current 910 mA
Array 8 Current 24 mA
Array 9 Current 30 mA

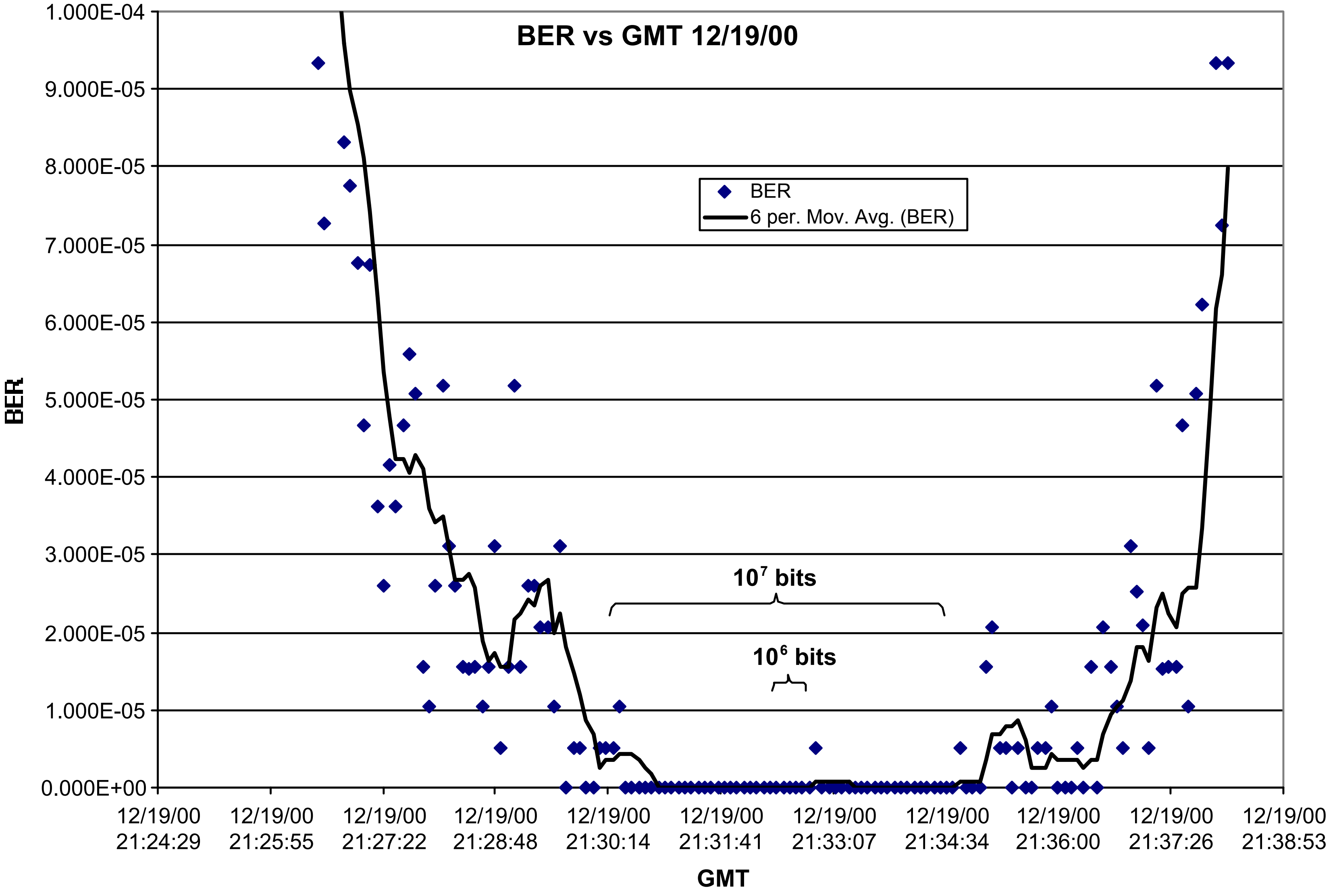
Bus Voltages

Bus A voltage 29568 mV
Bus B voltage 29568 mV
Bus B voltage 29656 mV

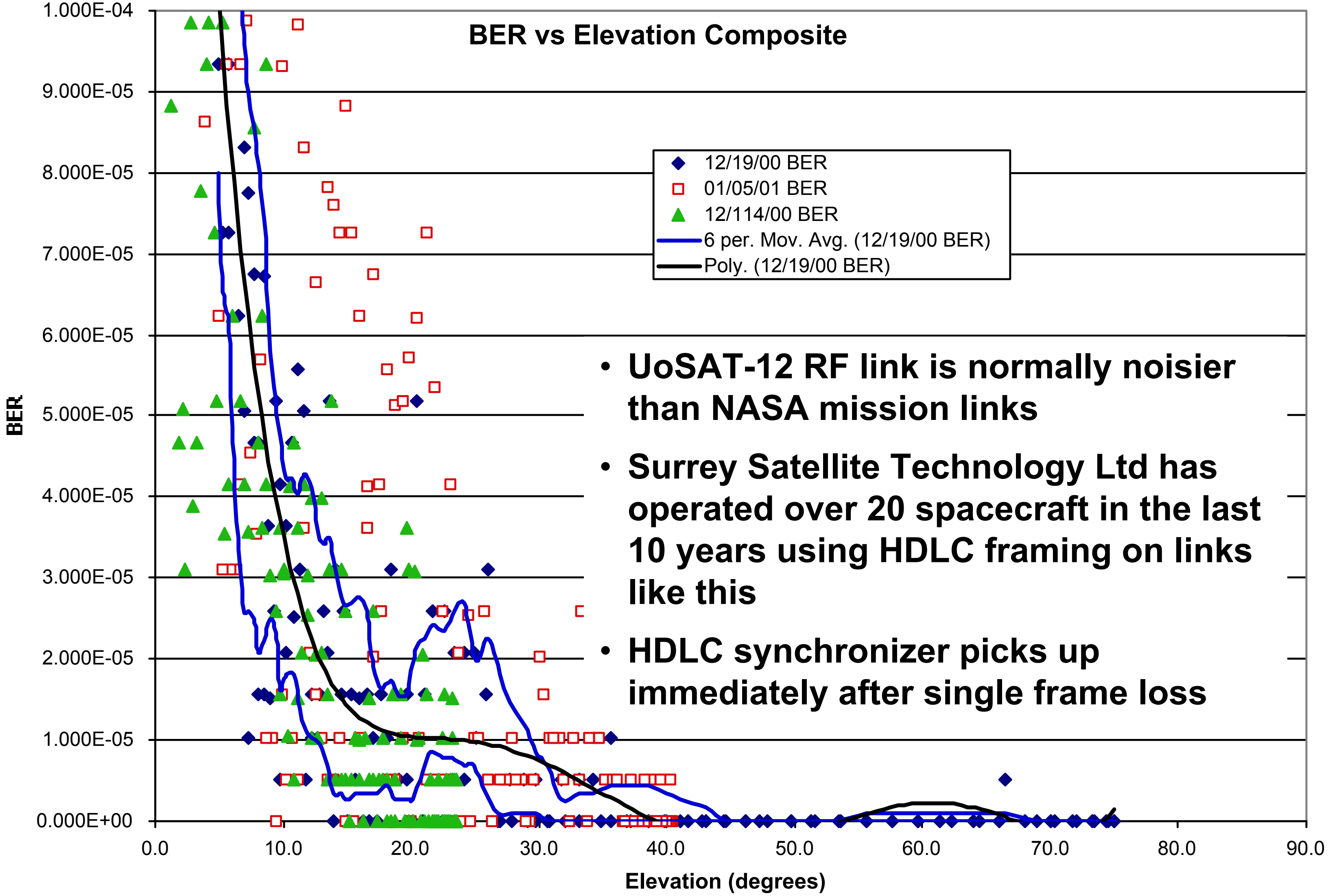
NavMag 1

NavMag 1 [X] –18429 nT
NavMag 1 [Y] –2926 nT
NavMag 1 [Z] 41659 nT

UoSAT-12 Link BER Tests



Composite BER Measurements



- **UoSAT-12 RF link is normally noisier than NASA mission links**
- **Surrey Satellite Technology Ltd has operated over 20 spacecraft in the last 10 years using HDLC framing on links like this**
- **HDLC synchronizer picks up immediately after single frame loss**

UoSAT-12 Tests Summary

- HDLC framing performed well over a noisy LEO link
- IP operates well over a noisy LEO link
- A standard BSD IP stack on a spacecraft works well
- UDP/IP supports return-only one-way links similar to those used by current spacecraft
- Standard TCP applications can be used over LEO spacecraft links
- With LEO spacecraft, the ground links are often worse that the space link

http://ipinspace.gsfc.nasa.gov/

(301) 286-3203

Acronyms

ATM	Asynchronous Transfer Mode
C&DH	Command and Data Handling
CCSDS	Consultative Committee for Space Data Systems
CFDP	CCSDS File Delivery Protocol
COTS	Commercial Off-The-Shelf
CSC	Computer Sciences Corporation
DSN	Deep Space Network
FDDI	Fiber Distributed Data Interface
FTP	File Transfer Protocol
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HDLC	High-level Data Link Control
ICMP	Internet Control Message Protocol
IP	Internet Protocol
IPSec	IP Security
LAN	Local Area Network
LZP	Level-Zero Processing
MDP	Multicast Dissemination Protocol
NASA	National Aeronautics and Space Administration
NFS	Network File System
NTP	Network Time Protocol
OS	Operating System
OSPF	Open Shortest-Path First
PI	Principal Investigator
POS	Packet over SONET
Power	Performance Optimization With Enhanced RISC
PPC	Power Personal Computer
PPP	Point-to-Point Protocol
RF	Radio Frequency
RIP	Routing Information Protocol
SMTP	Simple Mail Transfer Protocol
SNMP	Simple Network Management Protocol
SOMO	Space Operations Management Office
TCP	Transmission Control Protocol
TDM	Time Division Multiplex
TDRSS	Tracking and Data Relay Satellite System
UDP	User Datagram Protocol
VME	Versabus Modula Europa
VPN	Virtual Private Network
WAN	Wide Area Network
WFF	Wallops Flight Facility
WWW	World Wide Web