STS-107 Case Study:
End-to-End IP Space Communication Architecture

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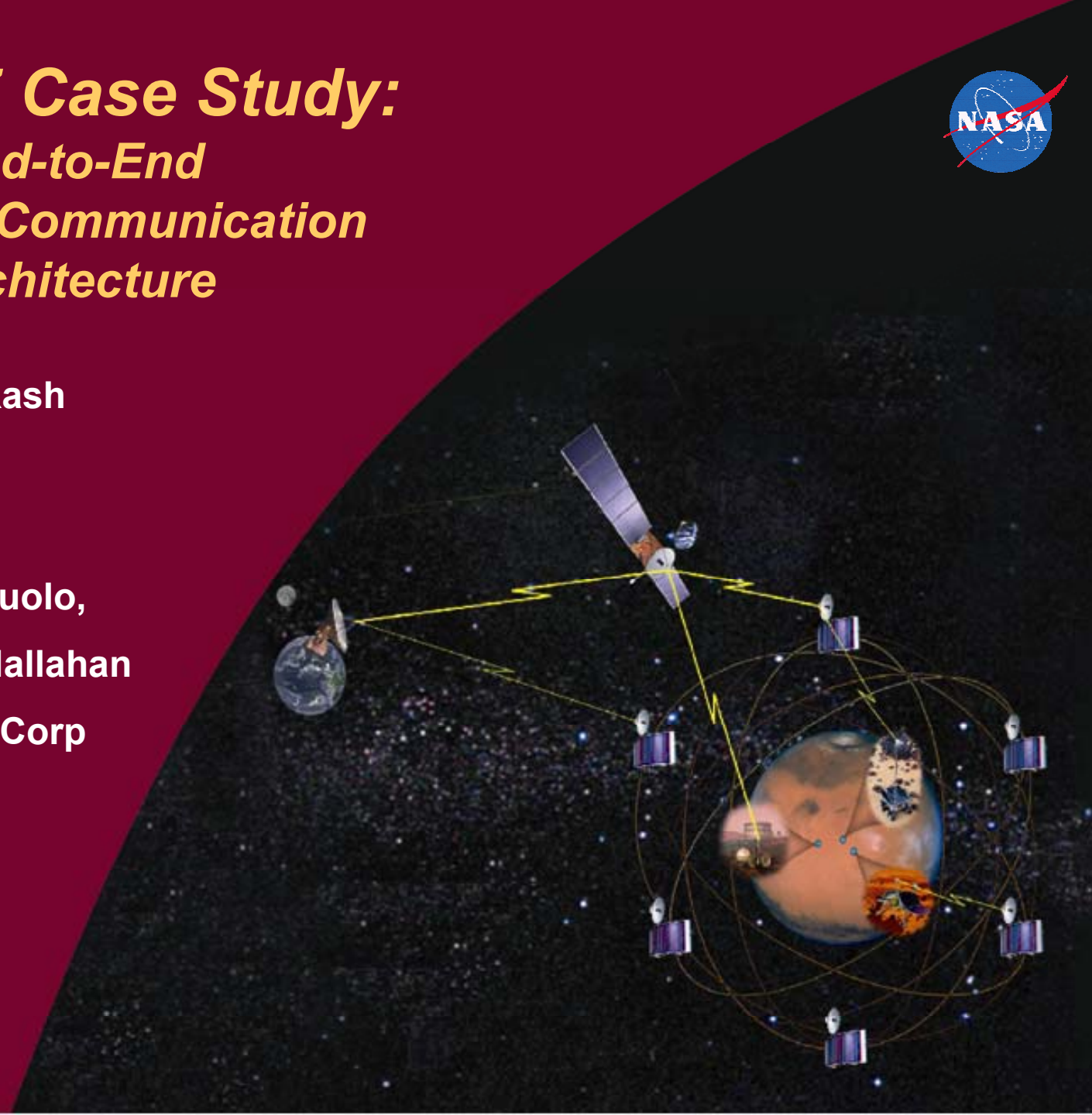
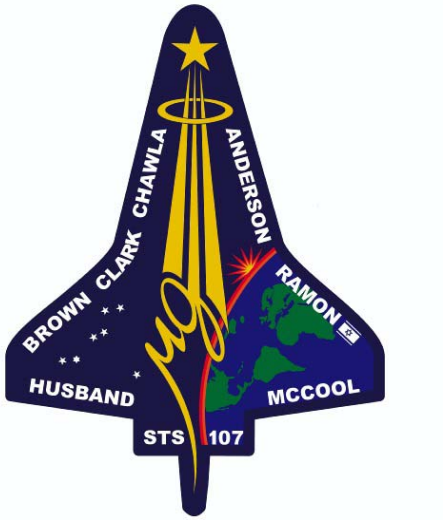


Overview



- The CANDOS Mission
- Space Components
- Ground Components
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- Protocols Tests
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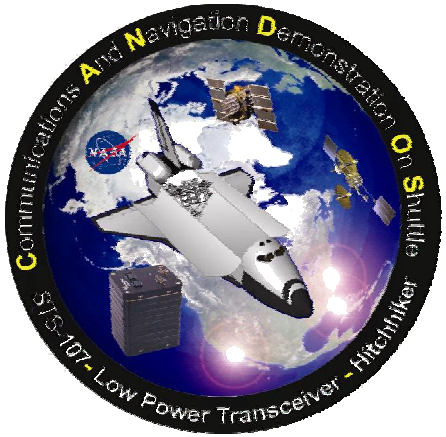
- Summary

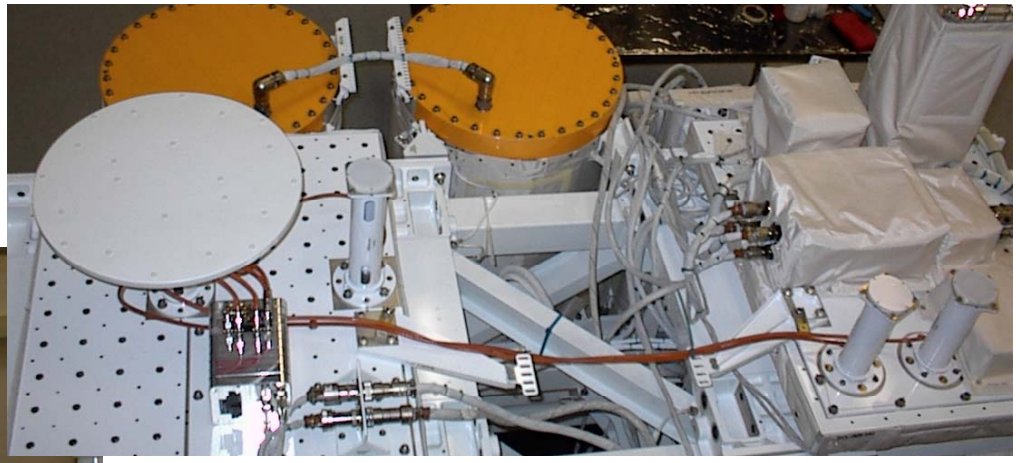


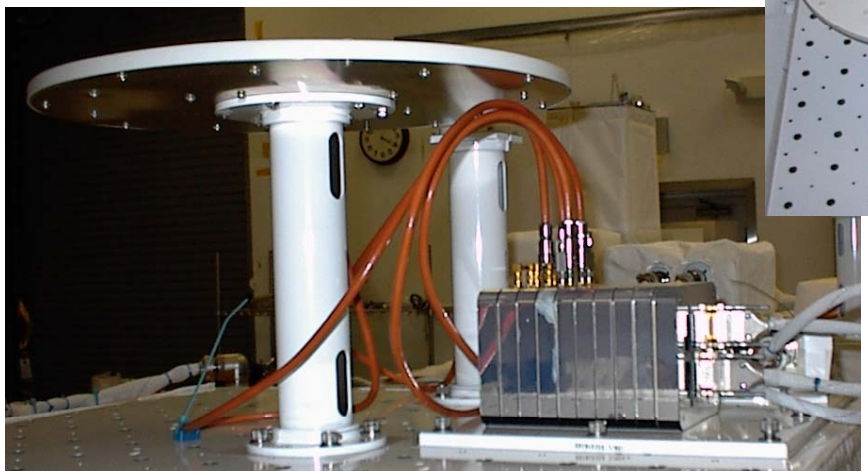
The CANDOS Mission

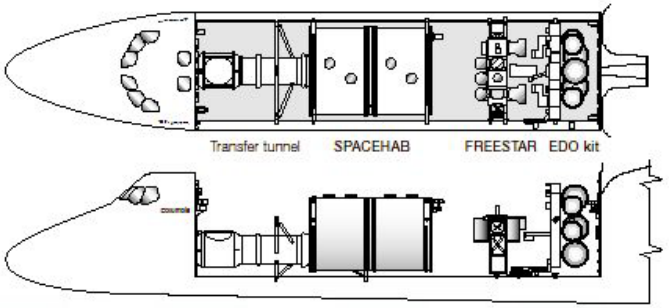
- **Communication And Navigation Demonstration On Shuttle (CANDOS)**
  - Hitchhiker payload on STS-107, January 16, 2003
  - Part of the FREESTAR (Fast Reaction Experiments Enabling Science, Technology Applications, and Research) payload
- **Low Power Transceiver (LPT) space test**
  - LPT is a multi-channel, programmable transceiver
  - Supports Space Network (SN), Ground Network (GN), and GPS modes
  - Built on stackable PC104 form factor boards
  - Initial flight test of transmitter, receiver, and GPS capabilities
- **Internet Protocol (IP) tests in space**
  - Test wide range of standard Internet protocols over SN and GN
  - Primary test of Mobile IP protocol for space use
  - Secondary tests of NTP, UDP, MDP, FTP, SCP, SSH,and IP operations
- **Ground station upgrades**
  - Initial test of issues for upgrading SN and GN stations to support HDLC framing and Internet protocols on space links

Space Components

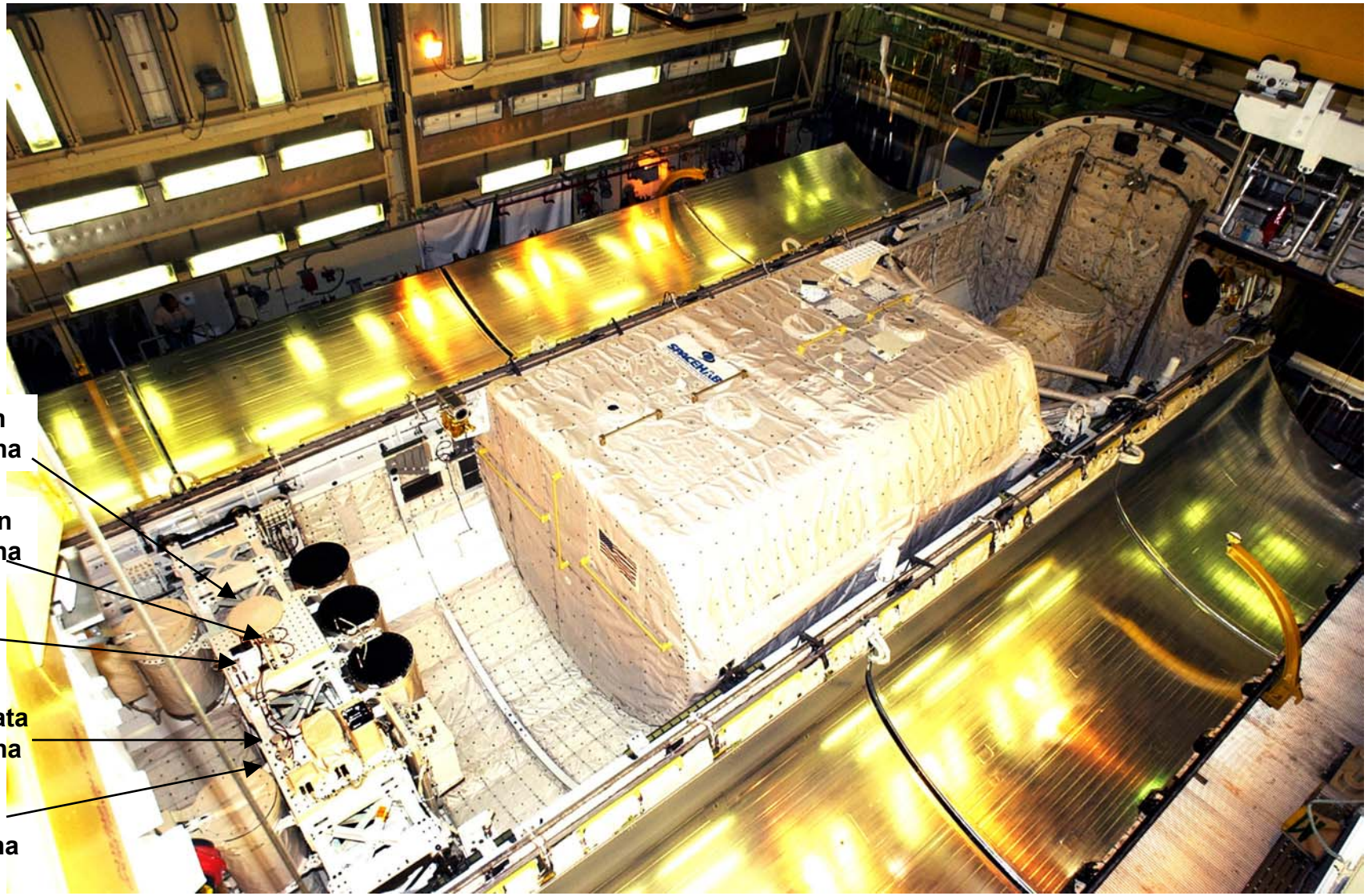
- **LPT Programmable Transceiver**
  - 2 - S-band transmitters
  - 12 - S/L-band receivers (SN/GN, GPS)
- **4 Antennas - high & low-gain transmit, low-gain receive, GPS**
- **233 Mhz 686 processor running Red Hat Linux 6.1**
- **PC104 dual sync serial interface between CPU and transceiver RS-422 clock/data**





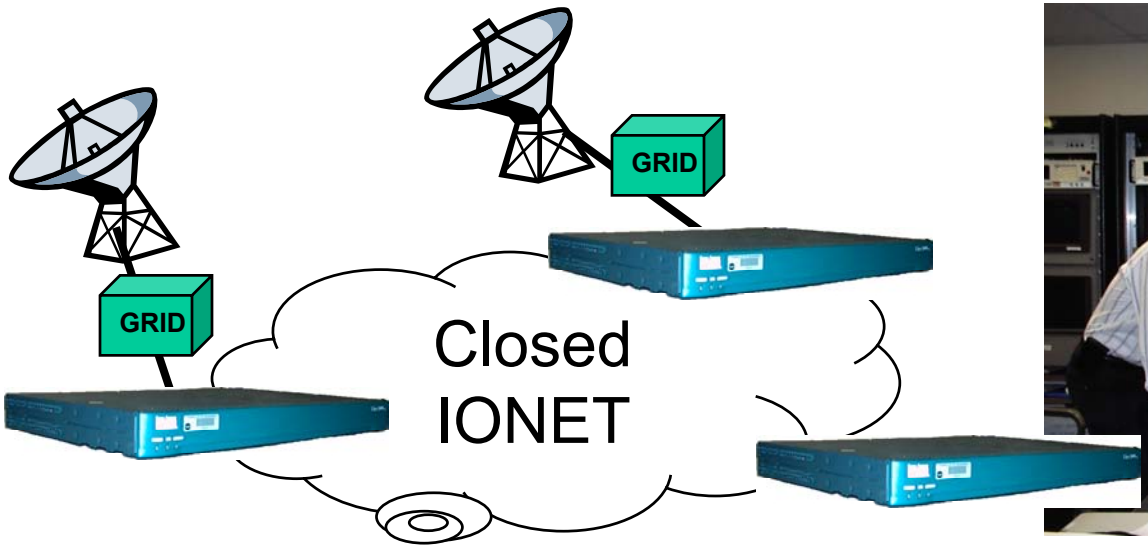


LPT in STS-107 Bay



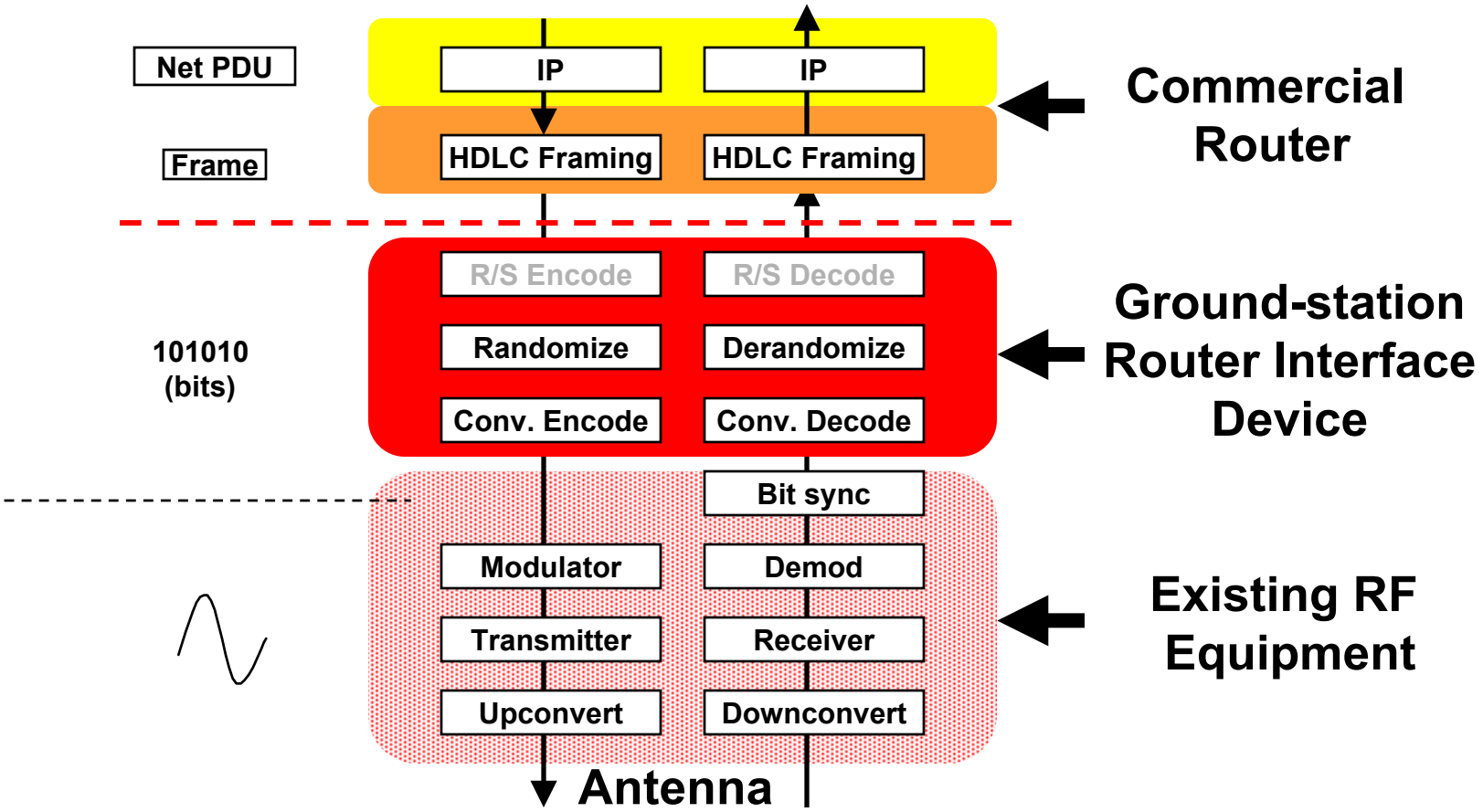
Ground Components

- Existing antennas, transmitters & receivers at White Sands Ground Terminal (WSGT), Second TDRSS Ground Terminal (STGT), Wallops, and Merritt Island Launch Area (MILA)
- RF equipment at stations connected to router serial ports
- Electrical interface adaptation and coding done with GRIDs
- Routers connected to NASA Closed IONET IP backbone
- Laptops and workstations in control center (Linux, MacOS, Win98)

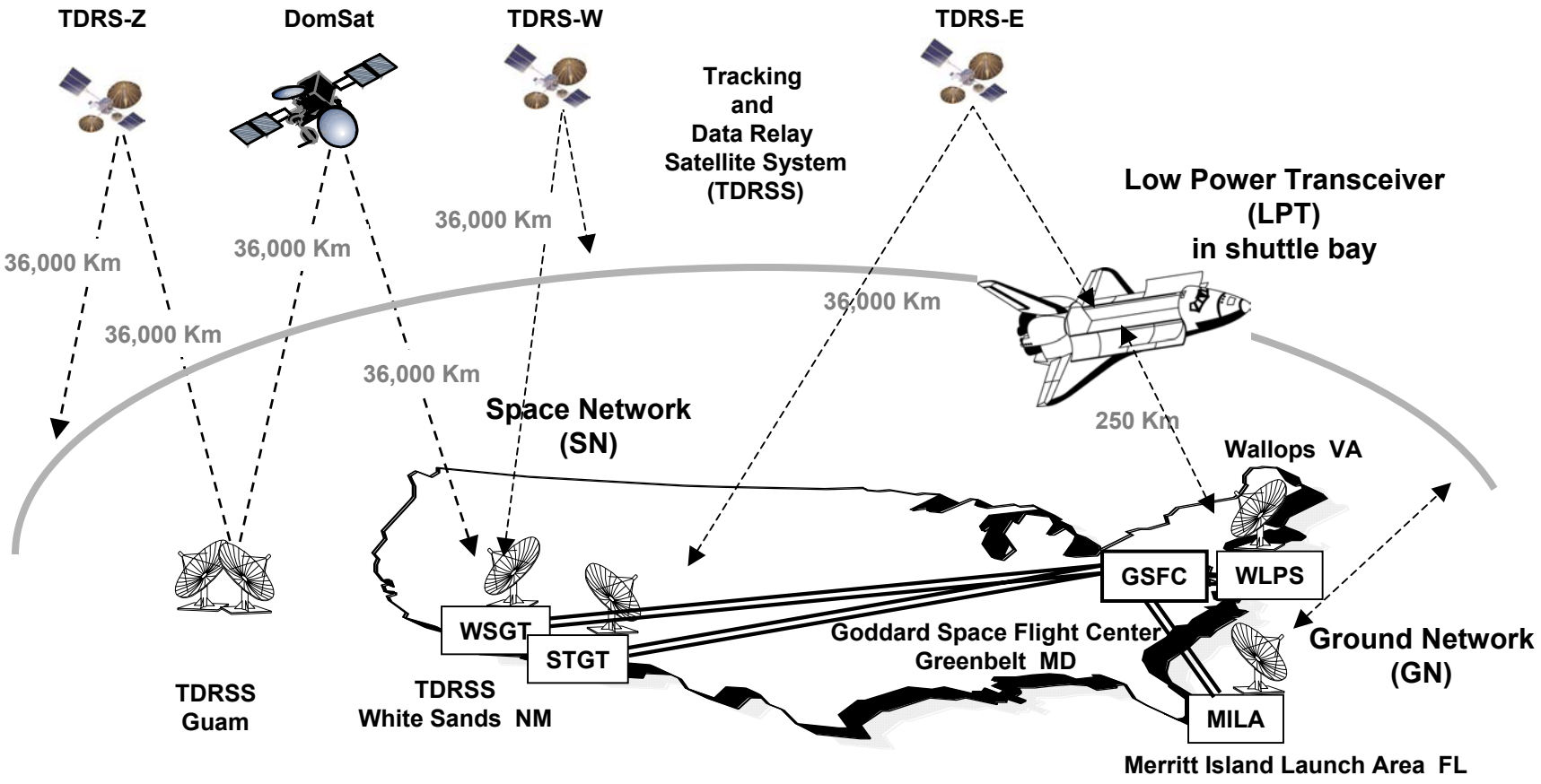


Space-Ground - IP Interface for Existing RF Equipment

- Device similar to a commercial satellite modem was needed to connect custom NASA RF interfaces to commercial routers (electrical interface and coding functions needed)



Mobile Network Connectivity

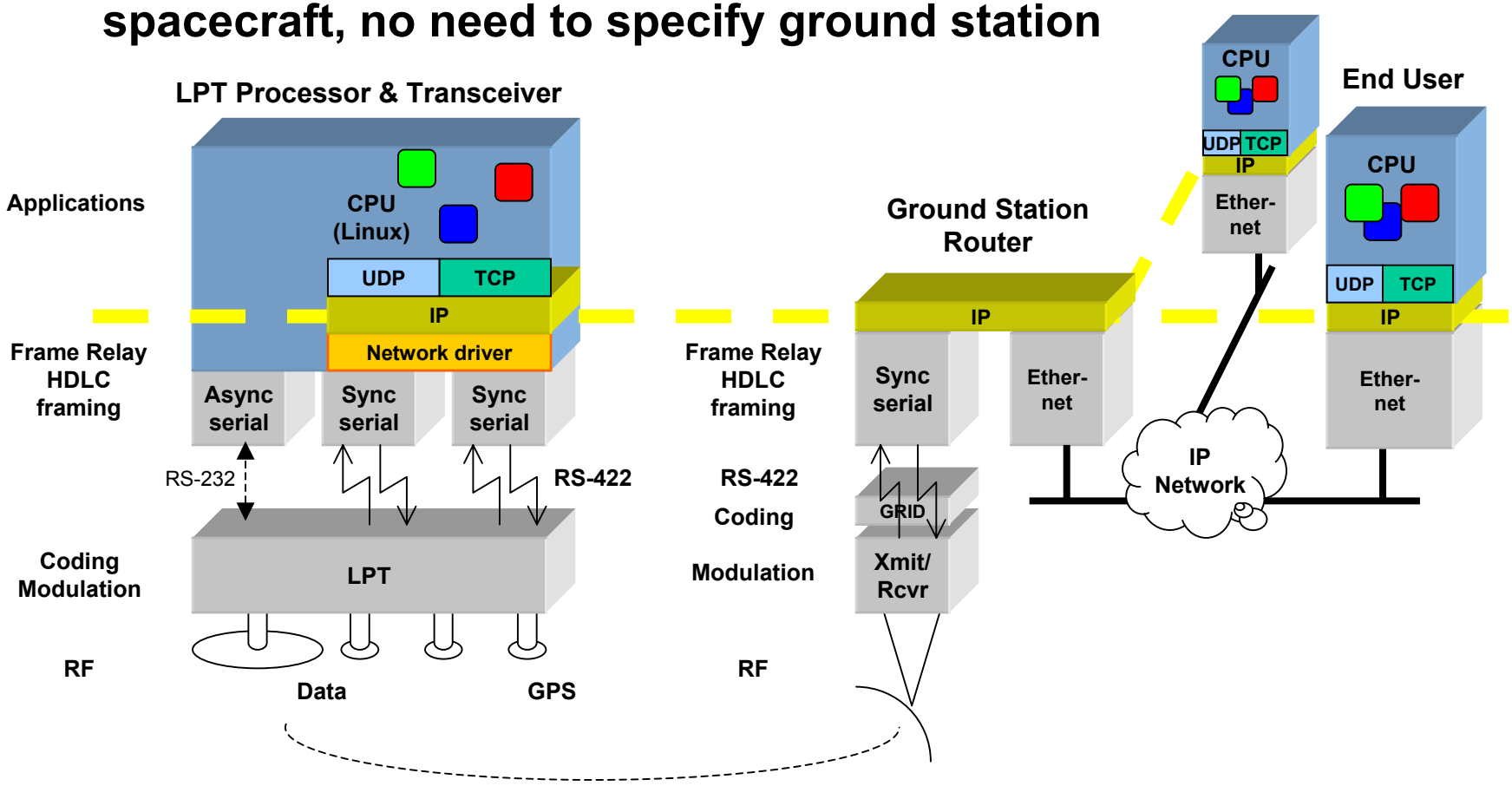


End-to-End Data Flows

- Standard applications use UDP and TCP APIs to communicate between LPT and end user systems
- Standard operating systems process IP headers
- LPT network serial driver connects onboard IP stack with RS-422 synchronous serial interface
- Frame Relay/HDLC frames over RS-422 clock and data lines between serial interface and LPT transceiver
- RF signal processed at ground and bitstream (Frame Relay/HDLC) fed to router serial port
- Ground IP packets delivered over NASA Closed IONET
- Data formats and protocols to the spacecraft were identical to those from the spacecraft
- LPT looked like any addressable Internet node

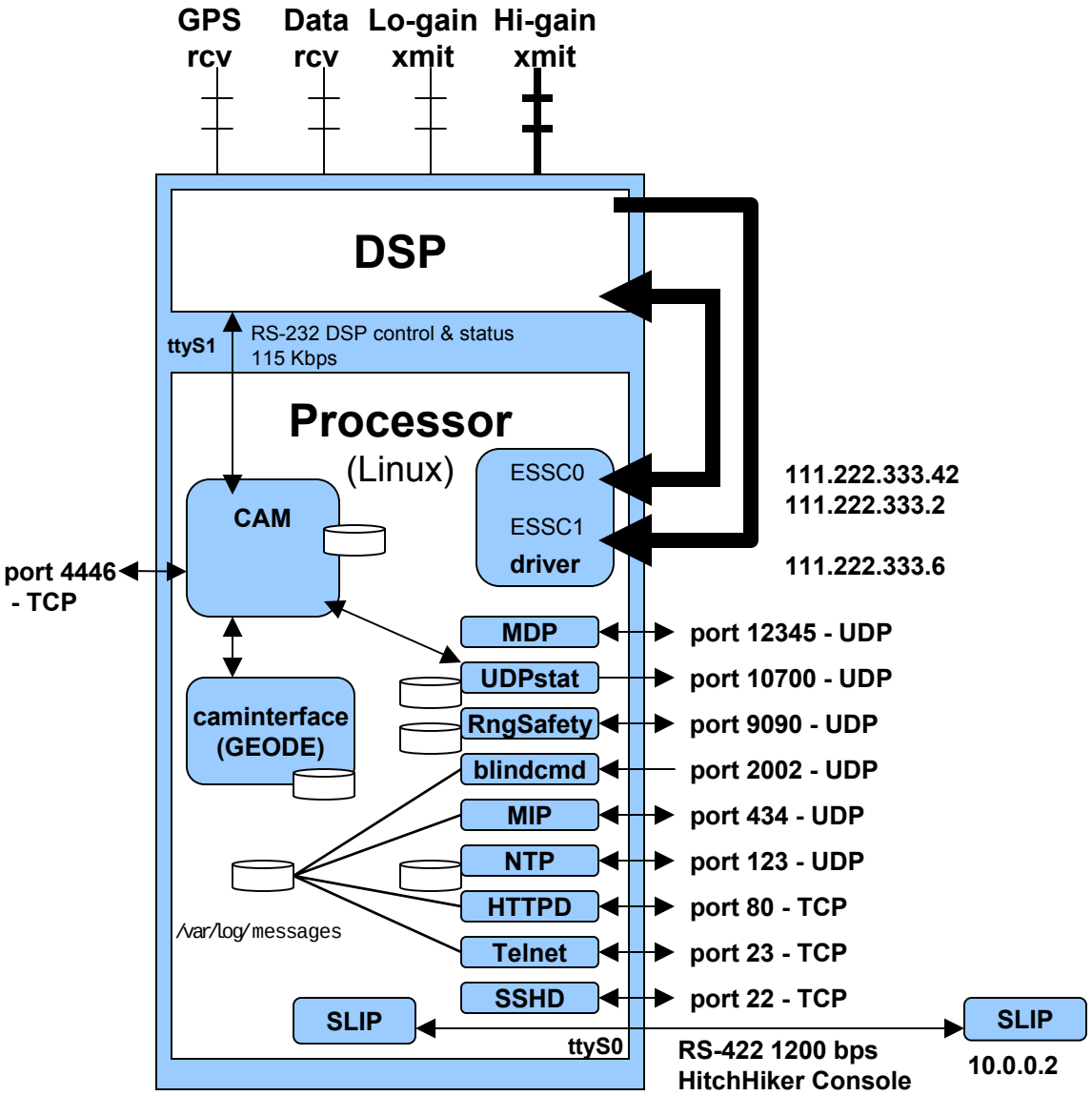
End-to-End Data Flow

- Data packets addressed directly to multiple destinations by onboard processor
- Multiple ground systems address data directly to spacecraft, no need to specify ground station



LPT Software Architecture

- Data directed to proper processes using standard and user assigned port numbers
- Status information logged to syslog and other files for later retrieval
- Different data kept separate from end-to-end
- More automated file management needed for future missions



Data Collection

- **Onboard LPT**
  - 10 sec. housekeeping status collected onboard and downlinked as real-time telemetry during communication contacts
  - All information timestamped in SYSLOG facility or application logs (NTP, GPS, MIP, BlindCmd, RangeSafety, etc.)
  - Manually compressed and moved log files to download directories
- **Network Monitoring**
  - PERL/SNMP program to monitor router interface traffic, data rates, error indicators, and MIP tunnel status
  - Ethernet LAN analyzer to log all packets in/out of control center
- **Control Center**
  - Captured LPT housekeeping telemetry, displayed it, and forwarded UDP status packets to multiple systems with LabView graphical status displays
  - Downloaded files collected and stored by pass for later analysis

IP Experiments

Experiment	UDP Protocols	TCP Protocols
Automated IP routing to current ground station antenna	Mobile IP- Automatically setup IP routing tunnels to multiple stations/antennas (SN and GN)	
Real-time Telemetry Delivery	UDP status packets - to monitor status of LPT over two-way and one-way links addressed to multiple destination addresses	
Onboard Clock Synchronization	Network Time Protocol (NTP) - synchronize and maintain onboard clock referenced to ground time servers	
Commanding	UDP Blind Commanding - Send UDP command packets to LPT over one-way uplink without Mobile IP or a two-way link	Secure Shell (SSH) & Telnet - login and control experiments from multiple locations
Reliable File Transfer	Multicast Dissemination Protocol (MDP) - perform reliable file transfer over both two-way and one-way communication links	Secure Copy (SCP) and File Transfer Protocol (FTP) - reliably transfer files to and from LPT during SN and GN two-way contacts

Security

- Security & Risk Analysis worked out with NASA network security group
- All data flows supported over the NASA Closed IP network that supports all other NASA missions
- All equipment configured and run through security scans before connecting to network
- Mobile IP used authentication between MN-HA, and FA-HA
- Encrypted login and data transfers using SSH and SCP
- One-way UDP paths out through firewall to Internet, no incoming Internet traffic allowed

Overall Protocol Results

- **HDLC framing performed well**
  - Variable length frames with CRC-16 error check
  - Operates over uncoded & convolutional coded links, various rates
  - ISO standard supported by standard router serial interfaces
  - Works over one-way links
  - Used over space links for over 20 years
- **Multi-protocol Encapsulation over Frame Relay**
  - RFC 2437 - IETF standard
  - Supported by standard routers and Frame Relay equipment
  - Works over one-way links
  - Serial line analyzers and protocol decodes available
- **UDP/IP packets well suited for space use**
  - Standard protocols supported by all routers and computers
  - No connection setup, each packet is self identifying and routable
  - Work over one-way links
  - Easy to pass out through one-way firewall paths
  - Worked for one-way blind commanding and status packets

Overall Protocol Results (cont.)

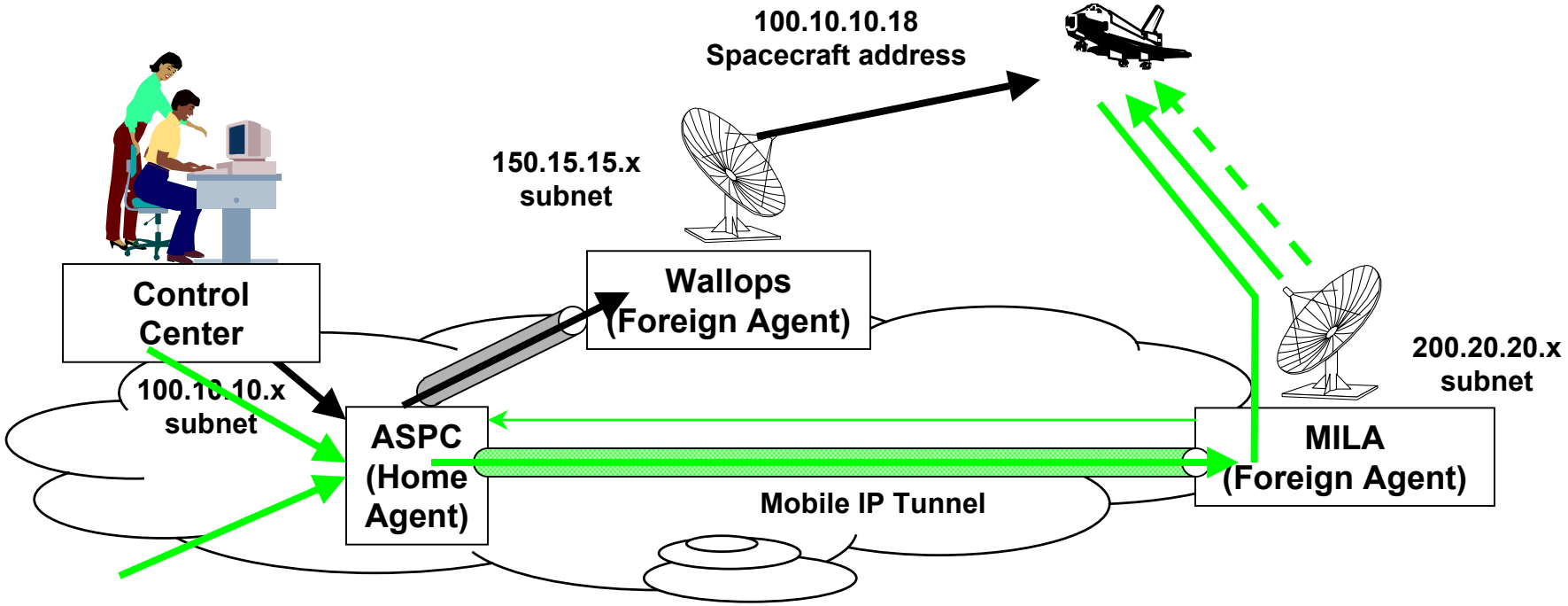
- **Mobile IP performed very well (~50 ms setup + RTT delay)**
  - Mobile IP registration set up tunnel as soon as two-way RF link was established (routers advertising every ~12 sec)
  - Mobile IP only required three packets to set up tunnel on marginal links (advertisement up, registration request down, reg. ACK up)
- **MDP file transfer protocol used extensively**
  - Supported transfers over one-way and two-way links
  - Allowed starting file downlinks before uplink was fully established
  - Independent of link bandwidth asymmetry and propagation delay
- **NTP functioned but needs more work for high precision**
  - NTP did maintain the processor clock and provided accurate time stamps for all system logs and telemetry samples
  - Didn't have good HW for precision timing , simple PC104 computer clock, no thermal control, no 1 PPS source,
  - No independent onboard time reference to measure against
- **SSH and SCP used successfully**
  - Required two-way link

UDP Telemetry Packets

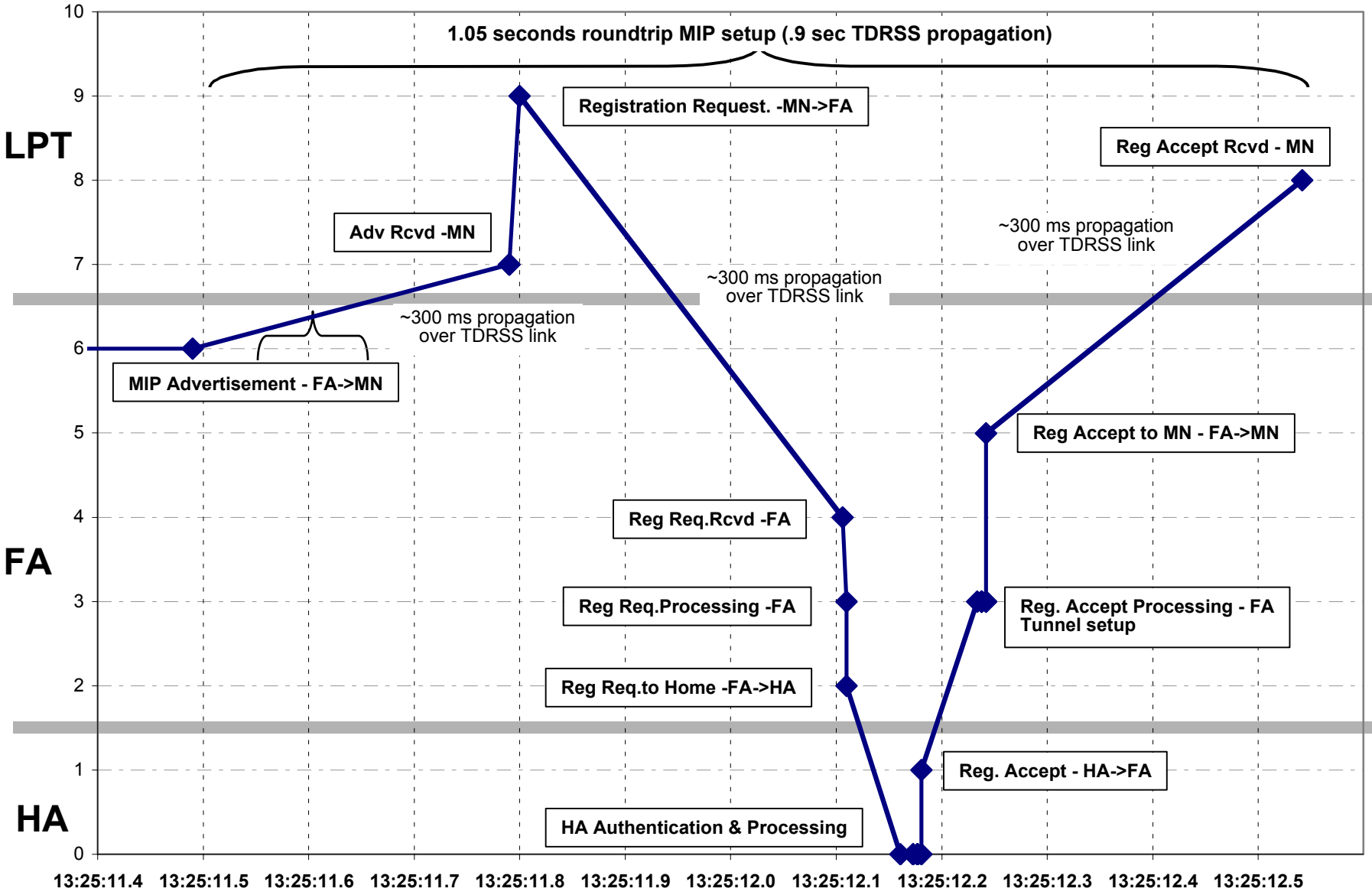
- **UDP packet uses in space communication**
  - Each packet has a full network source & destination address as well as UDP port number information to further categorize and route data packets
  - UDP unaffected by link delays and data rates
  - Functions properly without needing Mobile IP or two-way link
  - Current NASA data is carried around the ground in with CCSDS/4800BB/TDM in UDP packets
- **LPT real-time telemetry status packets**
  - CANDOS used simple tab-delimited ASCII strings to send real-time status data to specific ports on different systems for different types of data
  - Telemetry packet sizes variable from ~ 425-475 bytes depending on the numerical values in them
  - UDP packets delivered to open Internet via one-way only path through NASA firewall
- **UDP flexibility**
  - Different telemetry packets delivered to various destinations based on onboard addressing decisions.
  - Easily built status display programs using PERL, LabView, TREK

Mobile IP

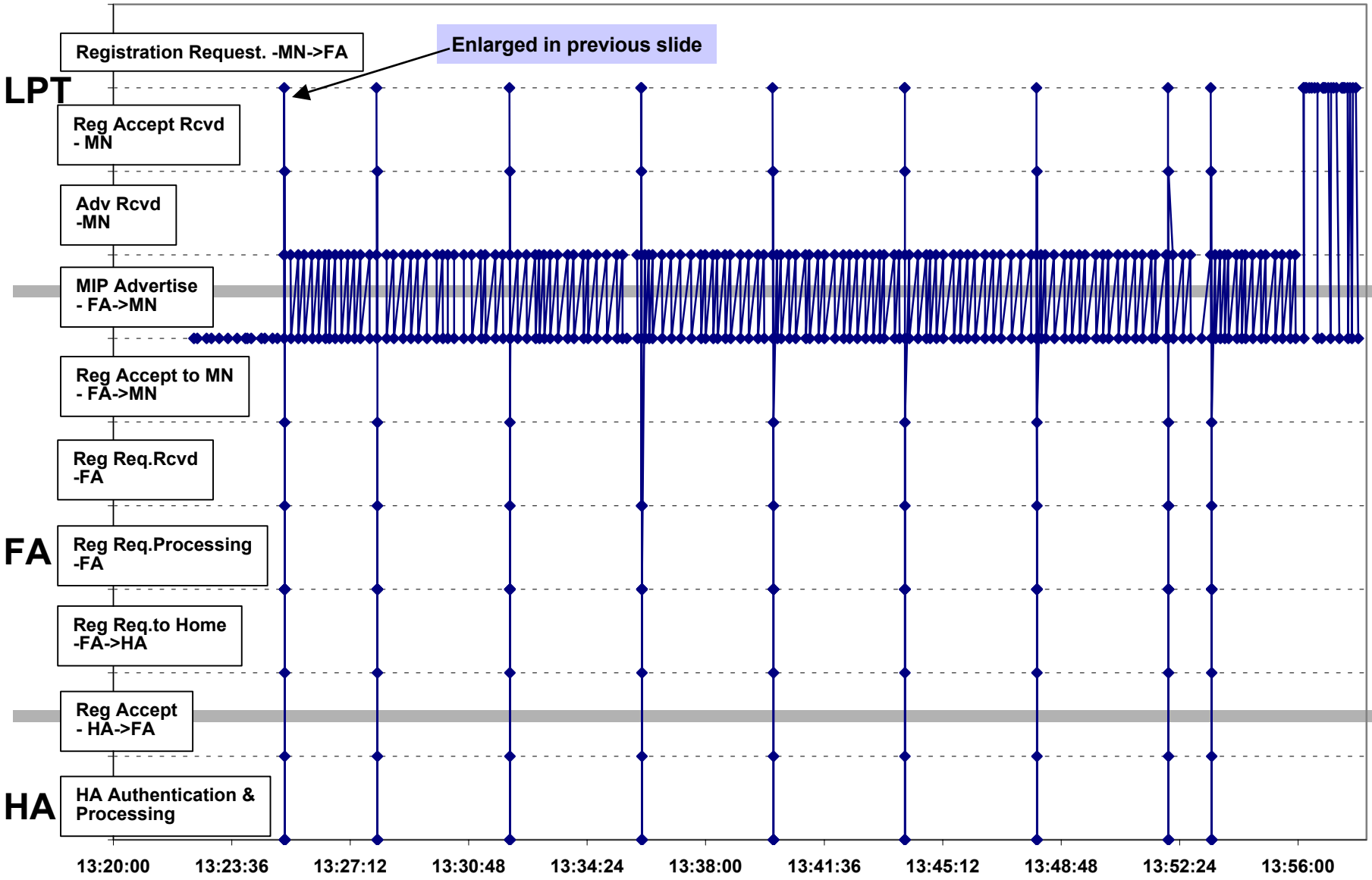
- Downlink data is routed normally
- Need to automatically determine which ground station to send commands through (same problem for cars, PDAs, laptops)
- Mobile device registration with ground agents supports automatic uplink routing configuration
- Robust protocol worked under non-optimal links, only needed to get 3 packets across the RF link to set up tunnel
- Cisco IOS 12.2.10



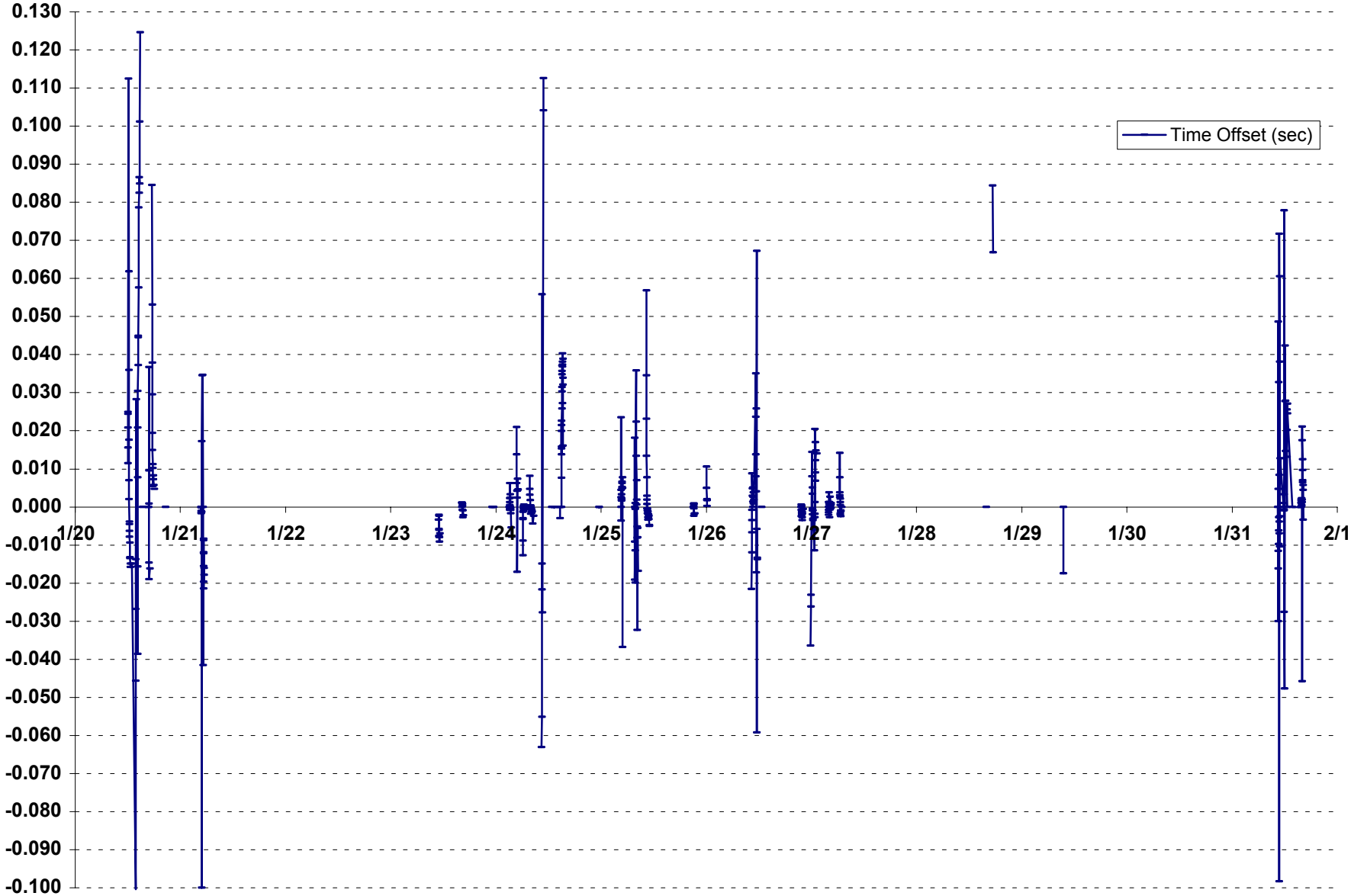
Mobile IP Performance



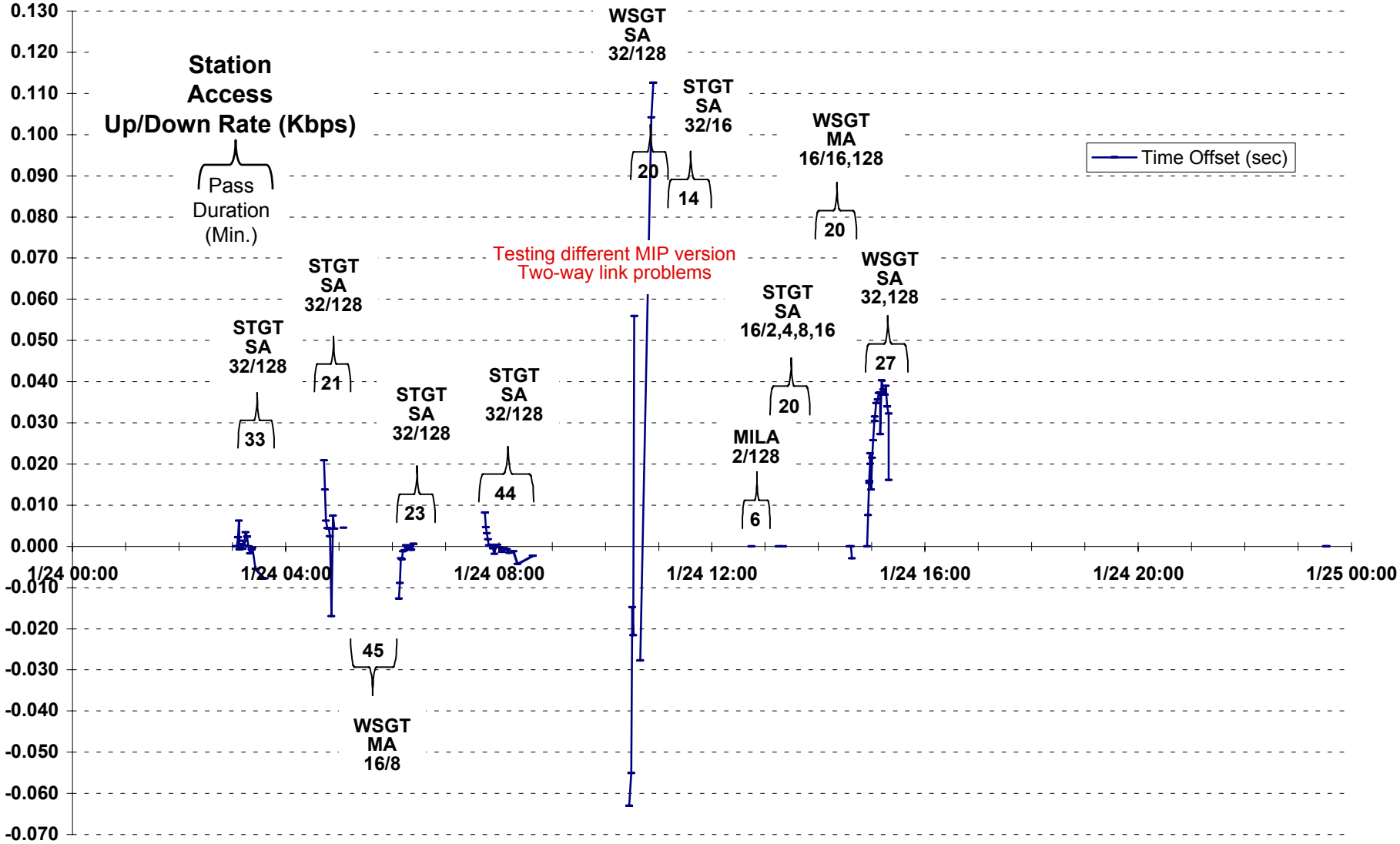
TDRSS Mobile IP Session



Network Time Protocol



NTP During Jan. 24, 2003



Commanding

- **Commanding using Linux shell scripts**
  - Shell scripts very useful for lots of last minute updates and fixes, onboard automation
  - Demonstrated using “cron” onboard to to execute scripts to perform some traditional time-tagged commanding
- **UDP**
  - Blind commanding over manual tunnel and automatic MIP tunnel
  - LPT process listening on port, received packet containing name of Bash script to execute and any parameters to pass to script
- **TCP**
  - Secure Shell (SSH) login - secure, encrypted login from multiple locations, some sessions with multiple, simultaneous access
  - Interactive onboard flight system maintenance
  - SCP uploads of scripts, and other configuration information (similar to table load and stored command uploads)
  - Telnet used across very slow HitchHiker 1200 baud access link since it had less overhead and was on a dedicated link

File Transfers

- **Data compression**
  - Some files were compressed with gzip (some 10 to 1 compression)
  - Others sent uncompressed if time and bandwidth available
  - File transfer applications unaware of compression, they moved files
- **UDP File Transfers**
  - MDP over one-way and two-way links, automated hot-directory
  - MDP across multiple ground stations with MIP handovers
- **TCP File Transfers**
  - Uploaded new executables, images, data, firmware
  - FTP used for special cases with limited bandwidth links
  - SCP sessions across multiple ground stations with MIP handovers
  - SCP over two-way links with multiple locations- control center, MSFC, OMNI lab (remote users didn't know what the path was)
  - MSFC picked up putty, public domain SCP software, the day before they downloaded files from the LPT to MSFC

Multicast Dissemination Protocol

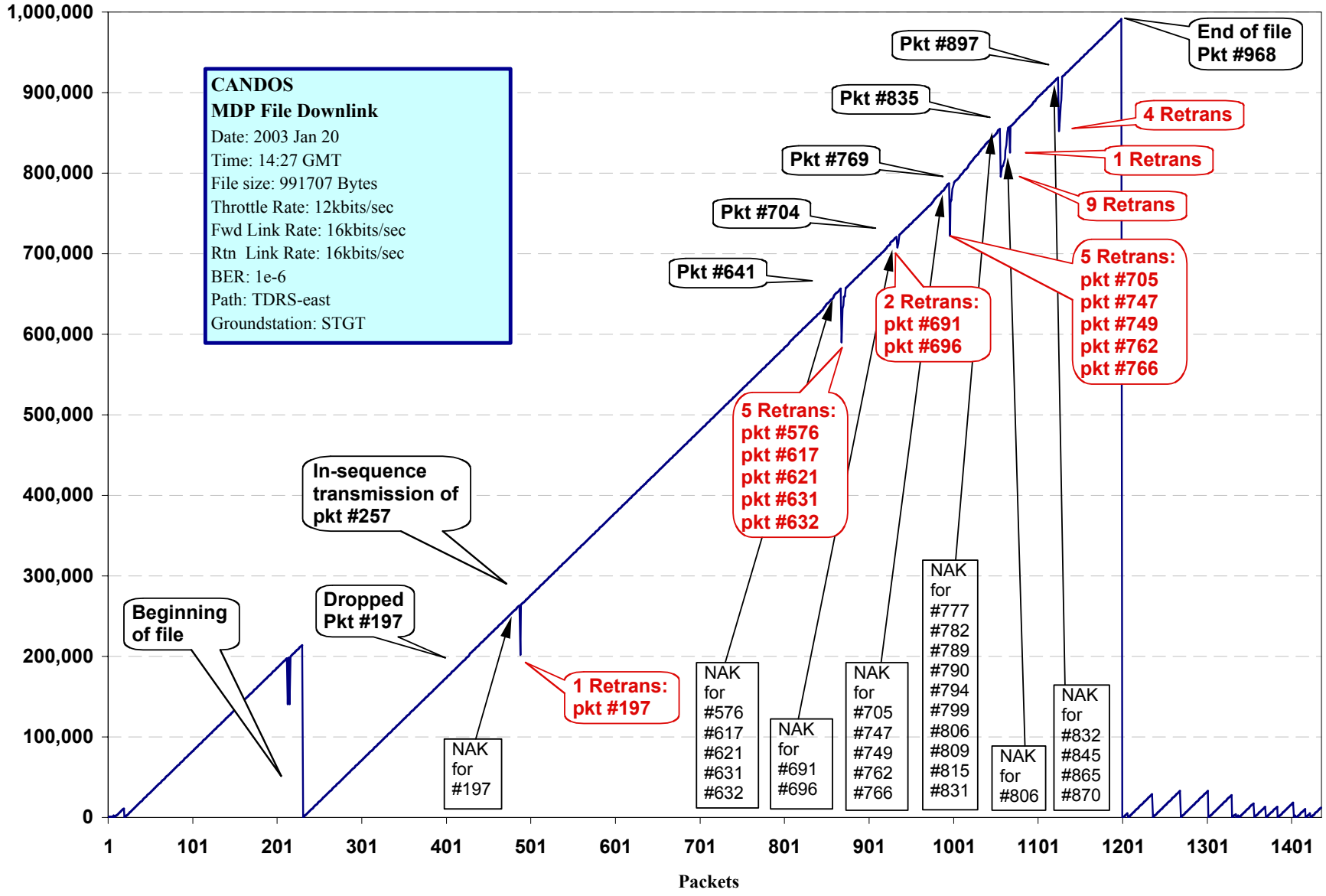
- UDP based, reliable file transfer protocol developed over 5 years ago at Naval Research Lab
- UDP protocol avoids TCP problems with delay and intermittent links and lets application deal with to space link delay and intermittent connectivity issues
- Multicast protocols developed to primarily send data to thousands of receivers and minimize responses using primarily NACKs and a final ACK
- On CANDOS MDP was also used over TDRSS MA Return-only links to deliver data with final NACKs, retransmissions, and ACKs during two-way contact time
- Work continuing as NACK Oriented Reliable Multicast (NORM) in IETF Reliable Multicast Transport Working Group

http://www.ietf.org/html.charters/rmt-charter.html

http://rmt.motlabs.com/

http://proteonforge.nrl.navy.mil/

MDP File Transfer Analysis



Anomalies

- **Software issues**
  - MosquitoNet MIP timeout handling software was not correct and long RTT with TDZ resulted in excess reregistrations
  - MDP throttle rate slow to change for low rates (fix coming)
- **Operational Issues**
  - Manual tunnel and automated tunnel conflict due to operator error
  - Coordination of multiple simultaneous users to avoid bandwidth conflicts, access control,
  - Onboard software configuration management is important with multiple user access
  - When SCP has trouble use MDP, more forgiving when two-way starts fading
  - Need to monitor/manage link utilization, excess UDP data can clog link and cause long delays, also triggered MIP excess reregistration

Operational Enhancements

- **This mission focused on testing protocols and functionality and a long-term operational mission would need more automation**
  - Ground network - automated setup and monitoring of manual IP routing tunnel for use in blind commanding
  - Automated onboard file management coordinated with file transfers and RF system
  - Connections between MIP, MDP and onboard transmitter/receiver status for automated operation
  - Automated error handling, space and ground
  - Mobile IP software implementation with better handling of long RTT
- **Possible onboard hardware/software enhancements**
  - Full router to do prioritized traffic queuing, security, mobile routing,
  - 1 PPS signal from GPS to drive onboard NTP daemon
  - More stable clock

Summary

- **Successful demonstration of using standard IP protocols and applications for space communication and operations**
- **Successful detailed measurement of protocol performance and operation with lots more data to analyze**
- **Successful demonstration of long-term, scalable concepts that can be used for command, control, and data collection for a wide range of future systems:**
  - satellite science missions
  - balloon and aircraft systems
  - ground sensors
  - collaborative/ad hoc systems with large numbers of devices
- **Internet protocols allowed us to quickly and easily try new applications and operation scenarios during the mission**
- **Standard, off-the-shelf products worked well and can work much better with a little design/configuration effort and real flight hardware**

Jan. 16, 2003 15:39:00 GMT

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