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Title: **Shuttle Payload Ground Command and Control – An Experiment Implementation for STS-107**

Abstract:

This presentation covers the design of a command and control architecture developed by the author for the Combustion Module-2 microgravity experiment, which flew aboard the STS-107 Shuttle mission. The design was implemented to satisfy a hybrid network that utilized TCP/IP for both the onboard segment and ground segment, with an intermediary unreliable transport for the space to ground segment.

With the infusion of Internet networking technologies into Space Shuttle, Space Station, and spacecraft avionics systems, comes the need for robust methodologies for ground command and control. Considerations of high bit error links, and unreliable transport over intermittent links must be considered in such systems. Internet protocols applied to these systems, coupled with the appropriate application layer protections, can provide adequate communication architectures for command and control. However, there are inherent limitations and additional complexities added by the use of Internet protocols that must be considered during the design.

This presentation will discuss the rationale for the framework and protocol algorithms developed by the author. A summary of design considerations, implantation issues, and lessons learned will be presented. A summary of mission results using this communications architecture will be presented. Additionally, areas of further needed investigation will be identified.

Shuttle Payload Ground Command and Control

An Experiment Implementation
Combustion Module-2 Software Development, STS-107

Presented at the Space Internet Workshop III
Cleveland, Ohio
June 4, 2003

David Andrew Carek, P.E.

Combustion Module-2

Ground Command & Control

- **System Overview**
- **Design Considerations**
- **Protocol Overview**
- **Implantation Issues**
- **Lessons Learned**
- **Summary of Mission Results**
- **Areas for Further Investigation**

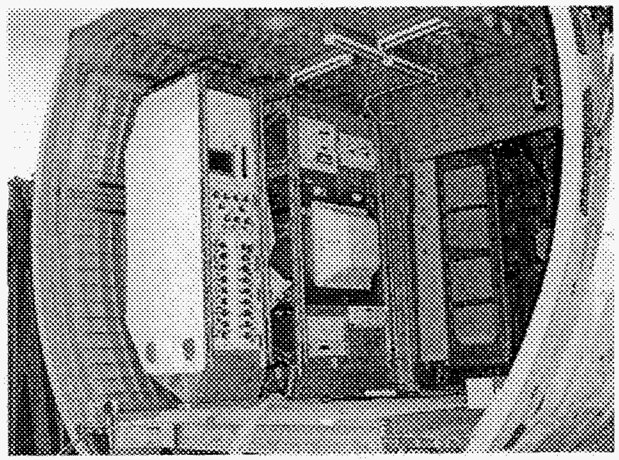
CM-2 Software Team

Top Row: Jonancy Colbrunn, Alan Richard, Steve Lux, Kevin Carmichael, Laura Maynard-Nelson, Lisa VanderAar, Dan Taylor

Bottom Row: Len Marinis, David Carek, Jeff Spiegler   Not Pictured: Richard Woodward, Kin Wong, Laszlo Szijarto

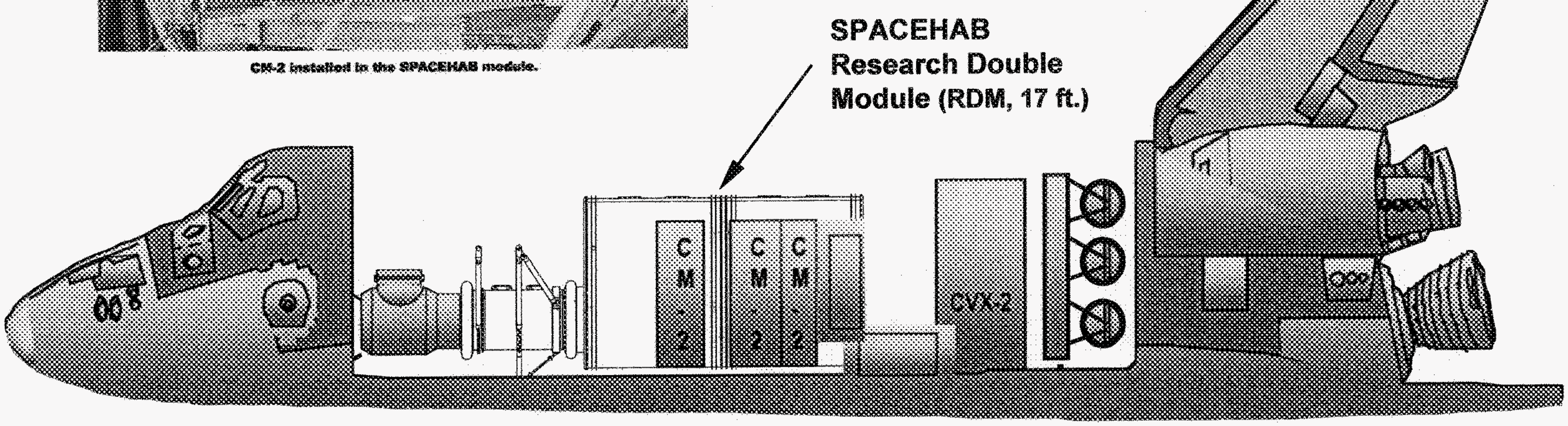
System Overview

SPACEHAB Carrier



CM-2 installed in the SPACEHAB module.

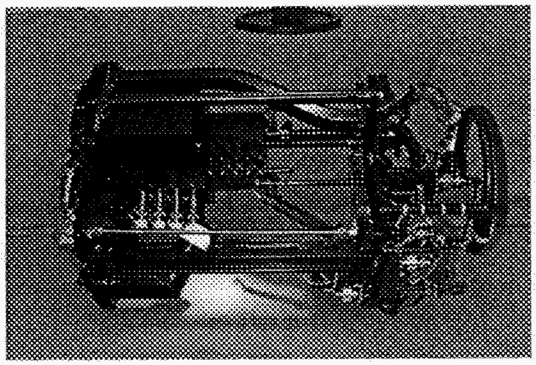
STS-107 SPACEHAB Payload Module Integration - Cape Canaveral

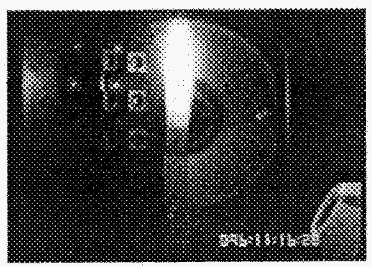


System Overview

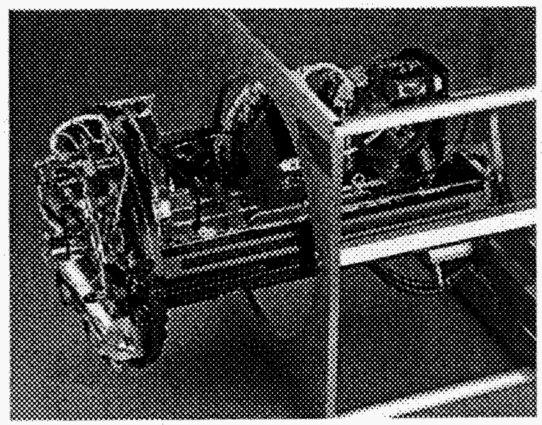
Microgravity Combustion Experiments

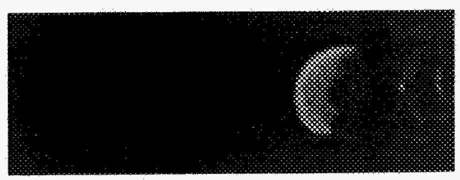
LSP



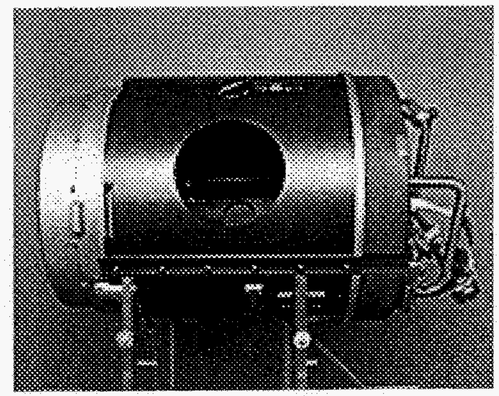


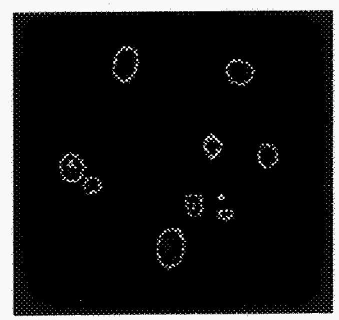
Mist





SOFBALL





See Ref. 1 for further information on these experiments

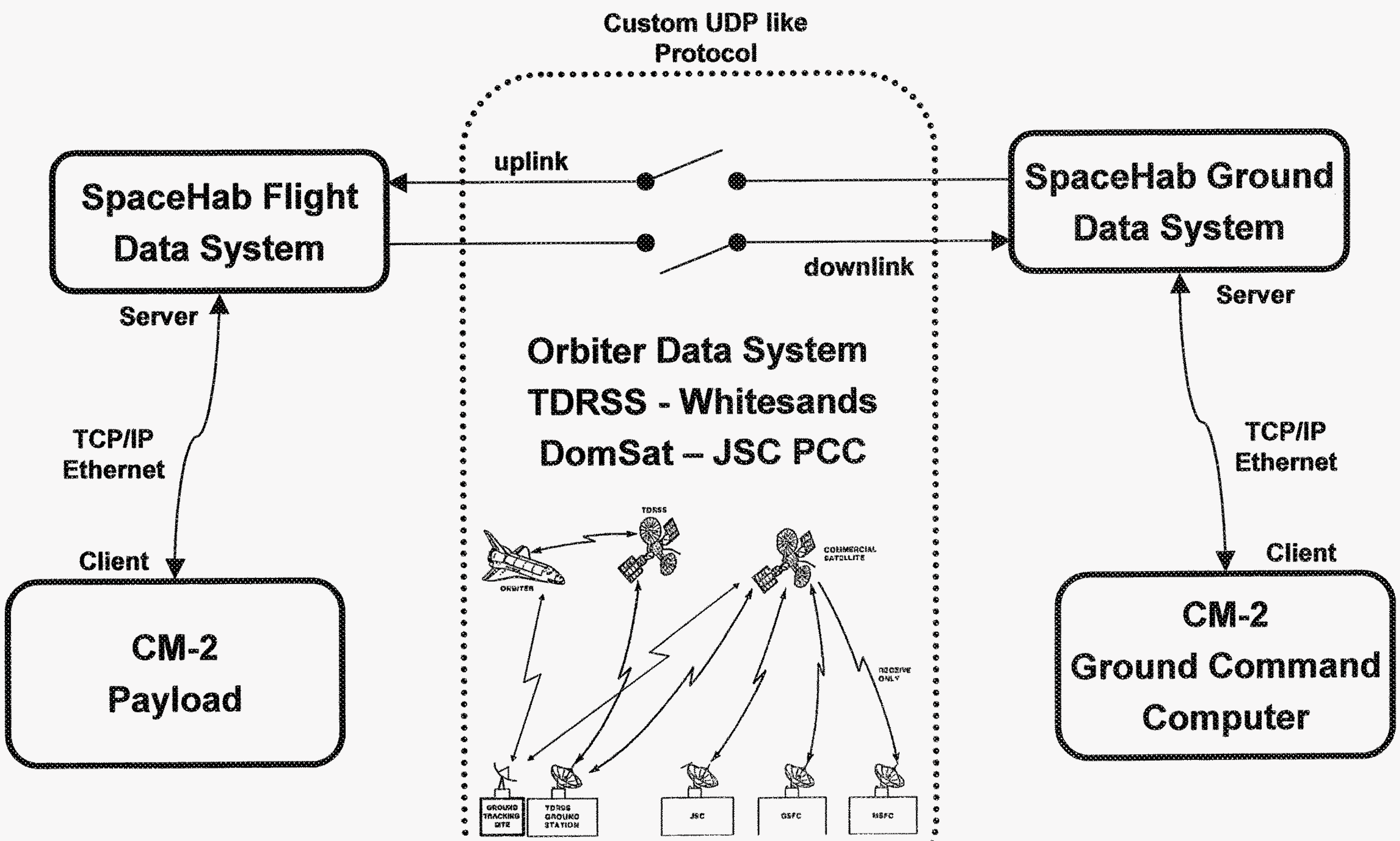
System Overview

Communications Interfaces SpaceLab/SPACEHAB

- SpaceLab - STS-83, STS-94
  - Main Computer I/F– RAU (Remote Acquisition Unit)
  - **Uplink Test Parameters Only**
- SPACEHAB – STS-107
  - Main Computer I/F – Ethernet
  - **Full Ground Commanding**
  - **File Downlink**

System Overview

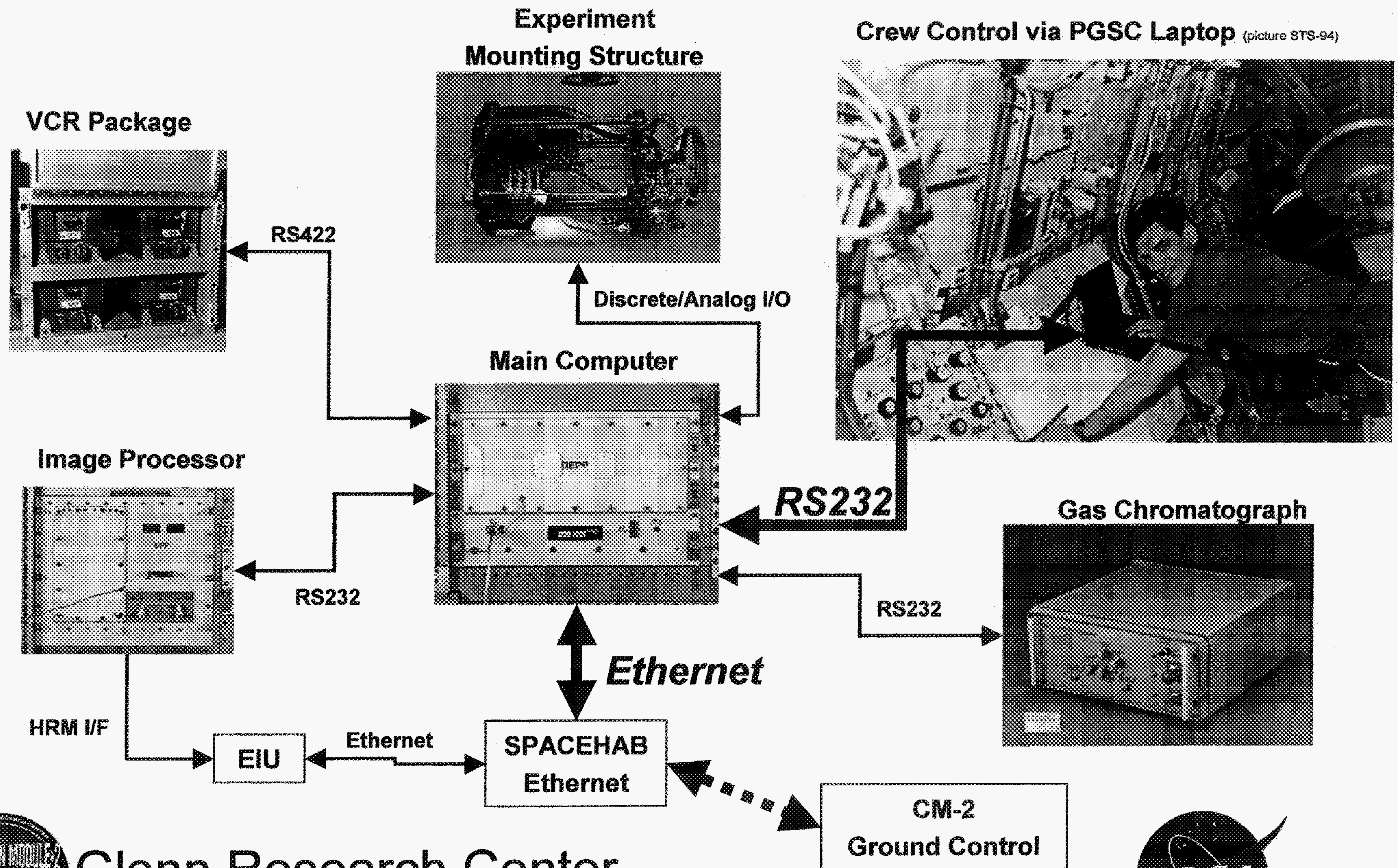
End to End Communications Path



Inset graphic source: Ref. 2

System Overview

CM-2 Payload Communications Interfaces



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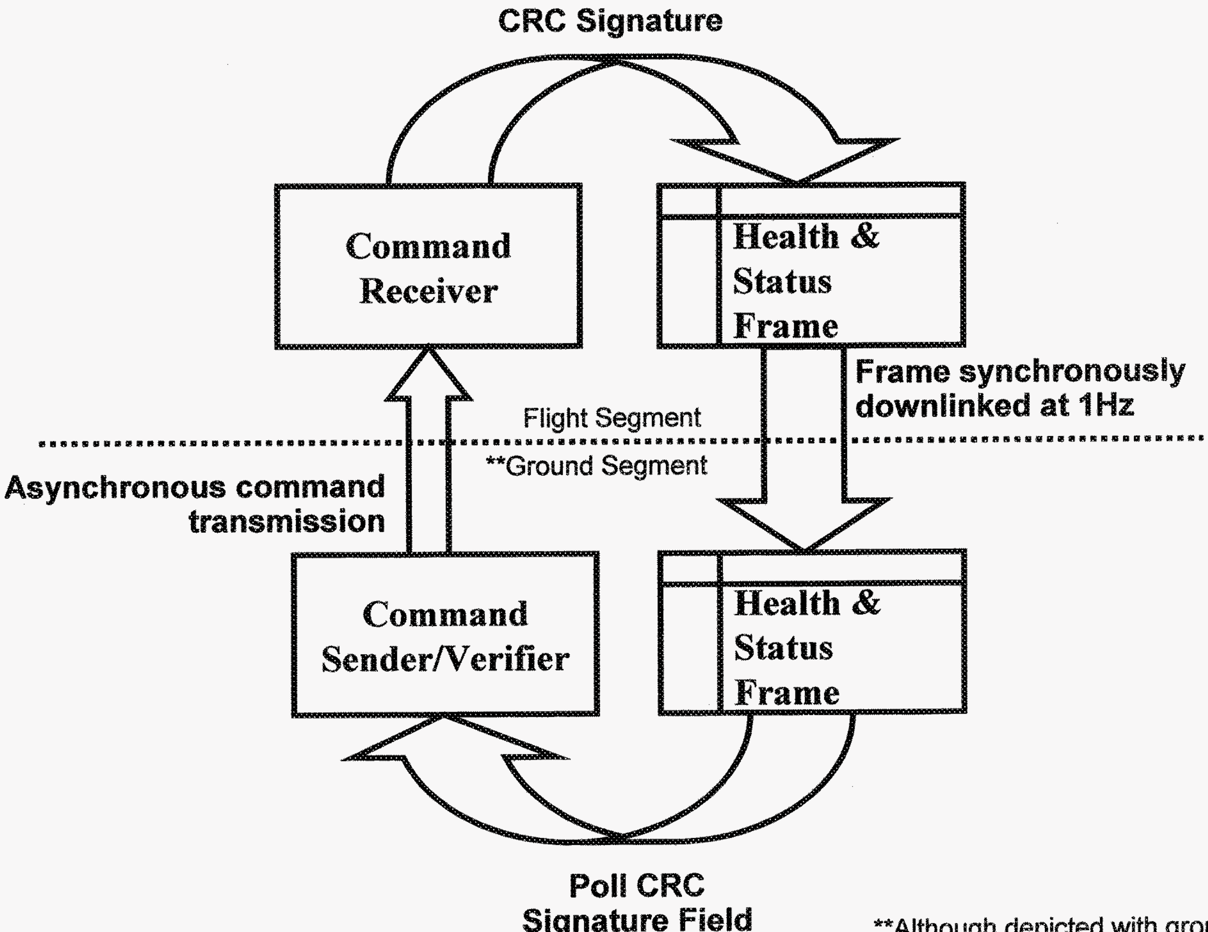
Communications Design Considerations

- Command Protocol Requirements
  - Flight computer must verify command integrity
    - No end-to-end TCP data integrity
    - Even if end-to-end, TCP checksum not good enough (Ref. 3,4)
  - Ground computer must verify command was processed
  - Must handle arbitrary data errors
    - Multiple bit errors
    - Partial/complete packet loss
    - Multiple consecutive packet loss
    - Long term or intermittent LOS
  - Must work for both PGSC (onboard) and ground commanding

Generic Command Verification Protocol Overview

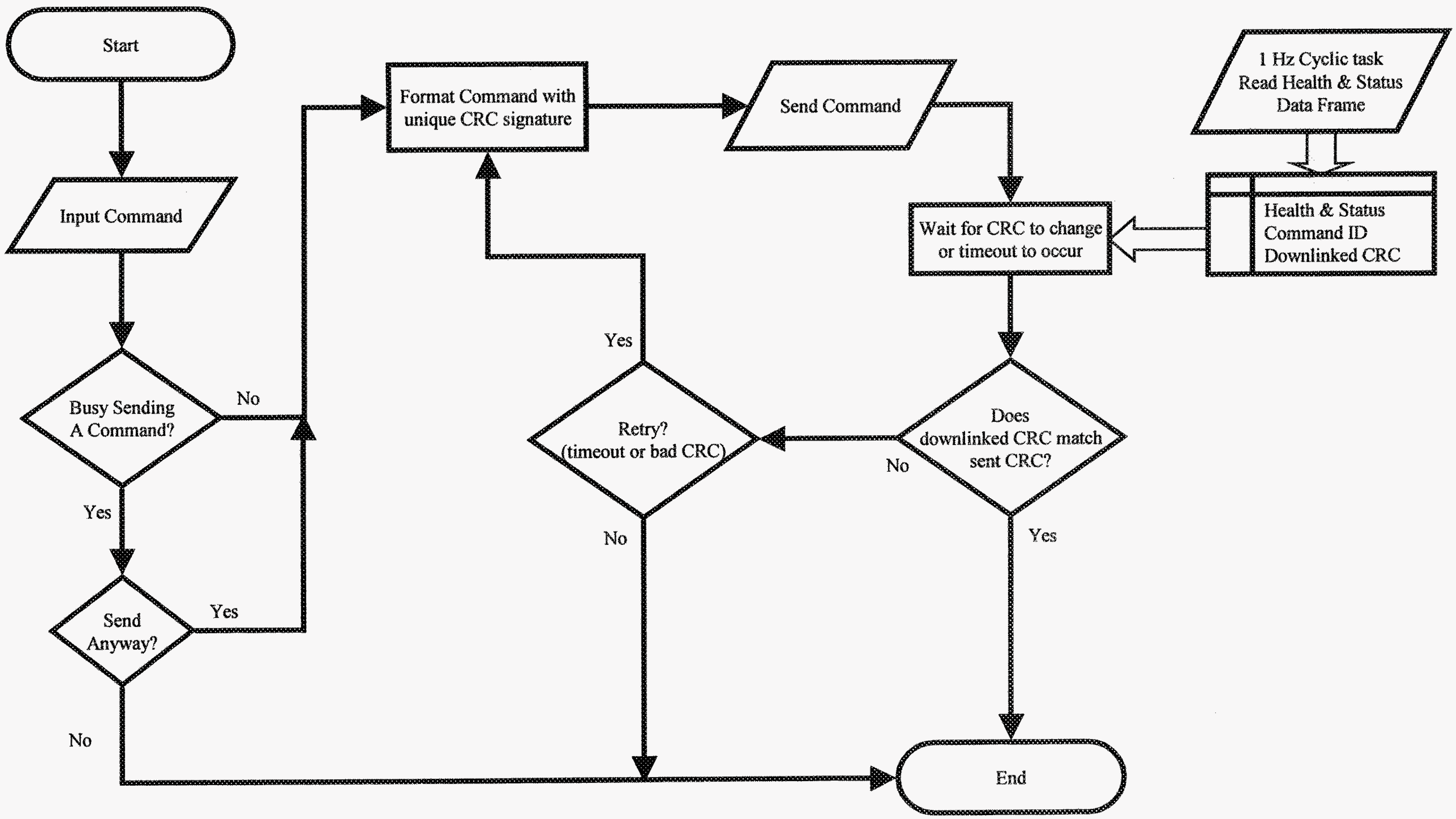


1. Command Sender generates unique CRC signature by appending timestamp to command prior to CRC calculation
2. Command Sender transmits command to Command Receiver
3. Command Receiver verifies command with CRC
4. CRC signature is statically inserted into the Health & Status data frame
5. Health & Status frame downlinked synchronously at 1 Hz
6. Command Sender waits to see CRC signature in H&S frame to verify command was processed

**Although depicted with ground command source, this is the same protocol that is used for onboard commanding with the PGSC over RS232

Protocol Algorithm

Ground Segment



Uplink Command Frame

- Uplink Command Frame Format

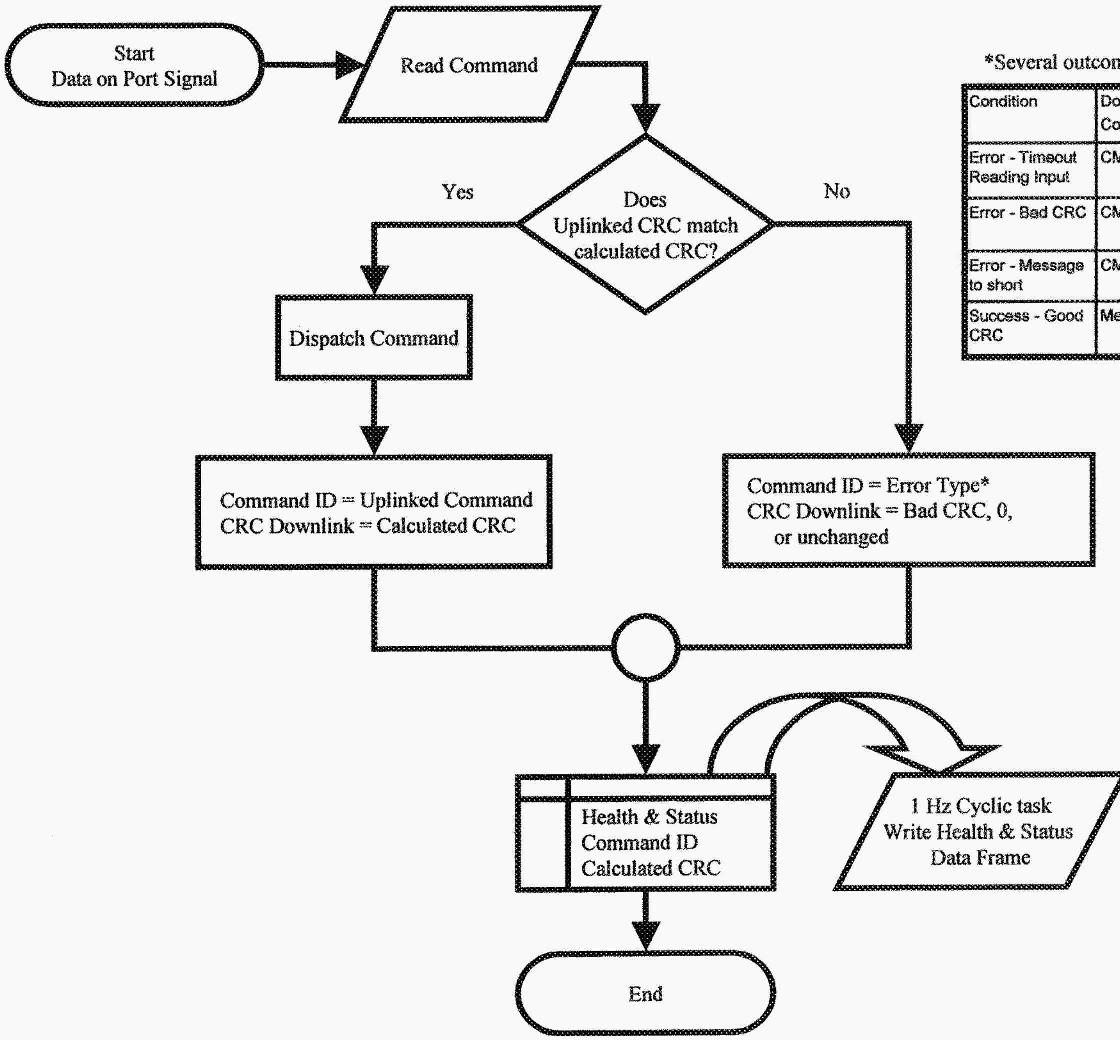
Cmd Type	Cmd ID	Data	Timestamp	32 bit CRC	CR

  - Command ID and command type both 16 bit
  - Data: optional and varable size (used mostly to uplink test parameters)
  - Timestamp 32 bit (milliseconds of uptime; wraps after 49 days)
    - Timestamp guarantees unique CRC signature for every command
    - Allows discrimination of duplicate command transmission
    - Alternatively a small (1byte) wrapping sequence counter could be used

- Command Encoding
  - Command generated in binary (including CRC)
  - Converted to hexadecimal ASCII string (0-9,A-F)
  - Carriage Return Record Terminator Added to hex string
    - Allows receiver to use simple readln call
    - Facilitates debugging (ASCII hex messages printable)
    - But … uses double the data bandwidth
  - Typically small command message size (nominally 25 bytes up to 256 bytes)

Protocol Algorithm

Flight Segment

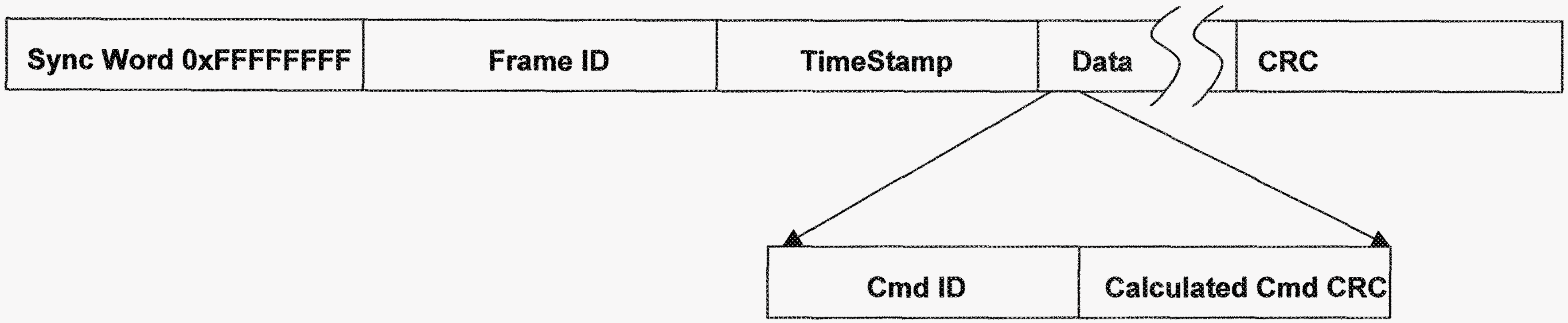


*Several outcomes of command read

Condition	Downlink Field Command ID	Downlink Field Calculated CRC	Cause
Error - Timeout Reading Input	CMD_READ_TIMEOUT	0	End of message lost (no terminator)
Error - Bad CRC	CMD_BAD_CRC	Calculated CRC (Bad CRC)	Corrupted data
Error - Message to short	CMD_BAD_CRC	Unchanged	Beginning of message lost
Success - Good CRC	Message Command ID	Calculated CRC (Good CRC)	

Downlink Data Frame

- Health & Status Engineering Frame Format
  - Binary to ground (300 bytes/sec)



- 32 bit sync word – picked least likely value to occur in data
  - CM-2 mostly 12 bit A/D's with upper 4 bits unused. Therefore 0xFFFFFFFF was an unlikely value to occur and good choice for sync pattern (could add alternating bit if potential for continuous stream of 0xFF)

Implementation Issues

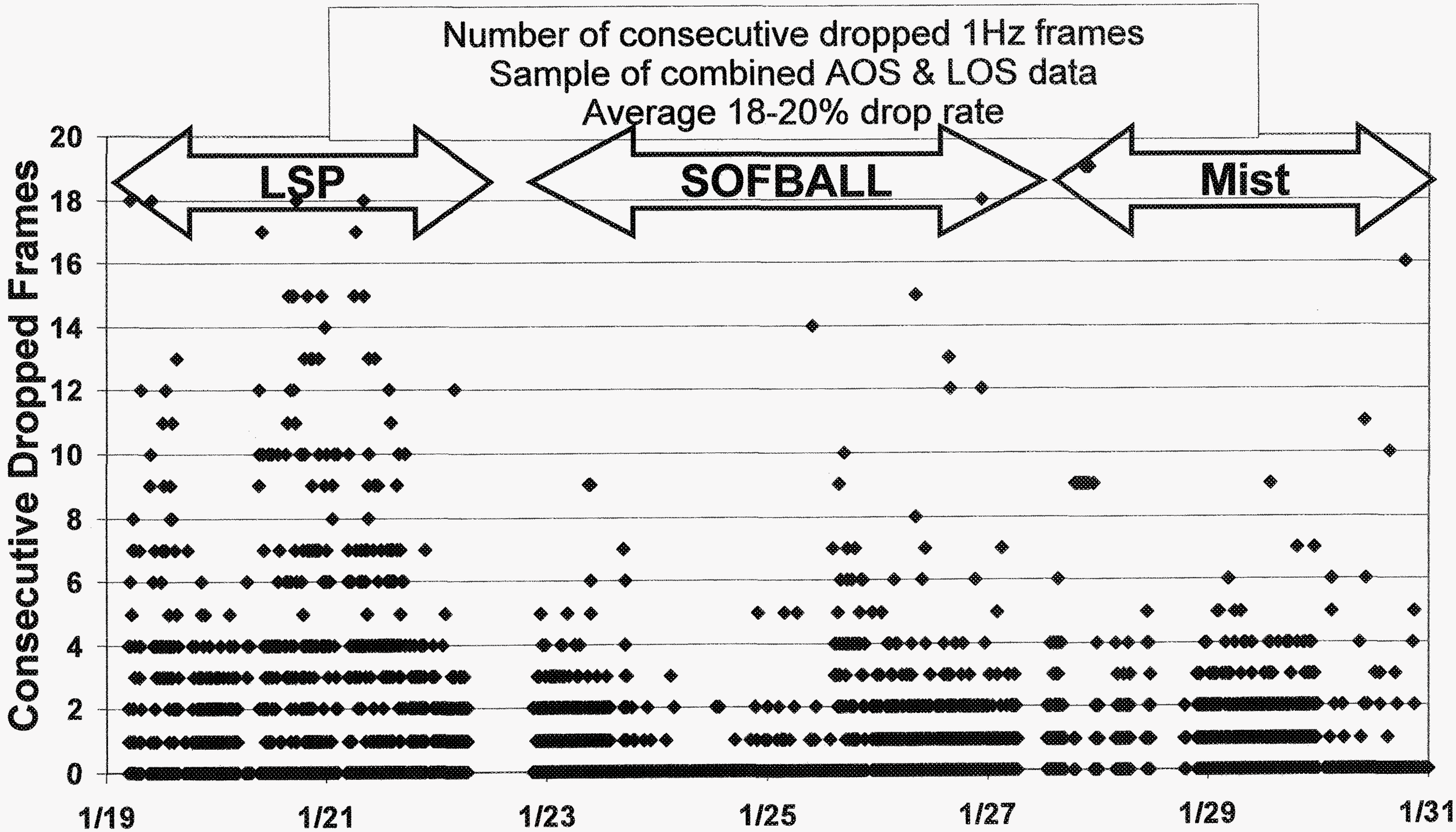
- Errors and Incompatibilities between TCP stacks
  - System crash on non-TCP packet reception
  - Problem with reconnects
- Data Packet boundaries not preserved
  - Stream preserved but packets arbitrarily fragmented
  - Parser initially designed for aggregation but not fragmentation (frames designed to fit within 1 MTU)
  - Required indexing search algorithm on CM data server (good practice anyway – TCP provides no record marker)
- Large queuing delay

Lessons Learned

- Use of TCP/IP in flight system
  - Doesn't relax testing requirements
    - sometimes makes problems more difficult to resolve due to lack of source code
  - Standards not implemented uniformly
  - RFC's hard to use as interface specifications
    - Significant cross referencing
    - Contains much more than may be used/needed by the system
  - Greatly enhances software development and testing
- Full integrated system tests required
  - Only tested on a per payload basis
  - SPACEHAB data system required patch during mission

Summary of Mission Results

Analysis of Health & Status Downlink



Summary of Mission Results

- High portion of Science data downlinked
  - LSP - 50%
  - SOFBALL - 65%
  - Water Mist - 90%
- Ground Commanding Results
  - No bad CRC's detected for commanding
    - SPACEHAB up/downlink included checksum
      - Bad data discarded (not forwarded to payload)
  - Commands uplinked = 1228
  - Unique CRC's in downlink = 1067
  - Average Round Trip Time = 10 seconds

Areas for Further Investigation

- Existing Architecture
  - Quality of service provisions
    - Examine use of TCP to throttle transmission rate
    - Examine impact to real-time OS
  - Worst case S-band latency not fully understood
  - Reduce queuing latency over S-band
- Revised Architecture
  - End to end design using UDP
  - Examine SCPS-TP or gateway architecture (ref. 5)

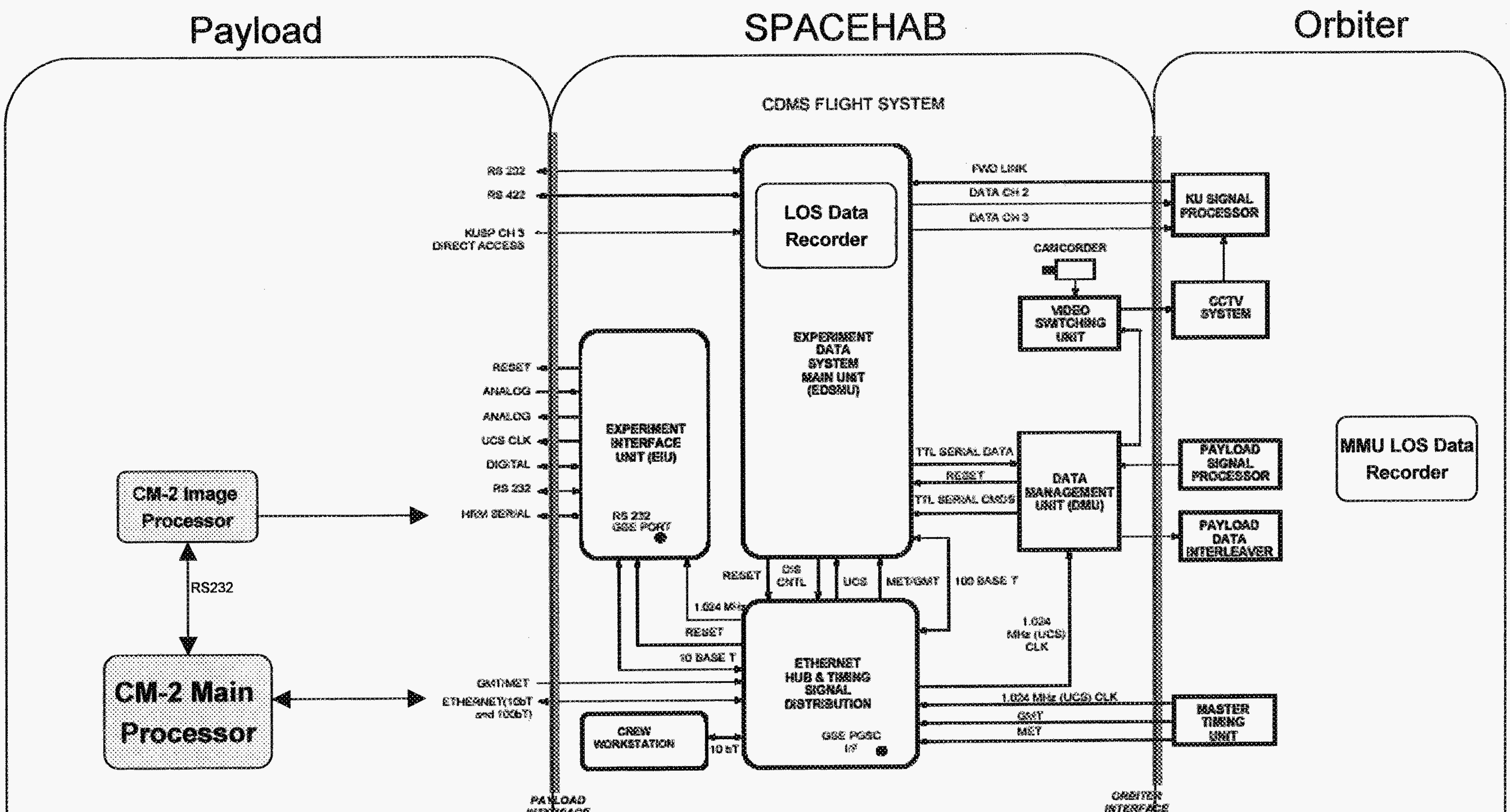
References

1. NASA GRC, http://microgravity.grc.nasa.gov/combustion/cm/cm_index.htm
2. NASA JSC, "Space Shuttle Program Payload Bay Payload User's Guide" NSTS 21492
3. Boeing, "SPACEHAB Experiment Interface Definition Document" MDC91W5023L
4. Stone and Partridge, "When The CRC and TCP Checksum Disagree", presented at ACM SIGCOMM 2000. http://www.acm.org/sigcomm/sigcomm2000/conf/abstract/9-1.htm
5. CCSDS, "Space Communications Protocol Standards (SCPS): Rationale, Requirements and Application Notes" CCSDS 710.0-G-0.4, http://www.scps.org/Documents/717x0b1.pdf

Extra Slides

System Overview

Flight Data Systems



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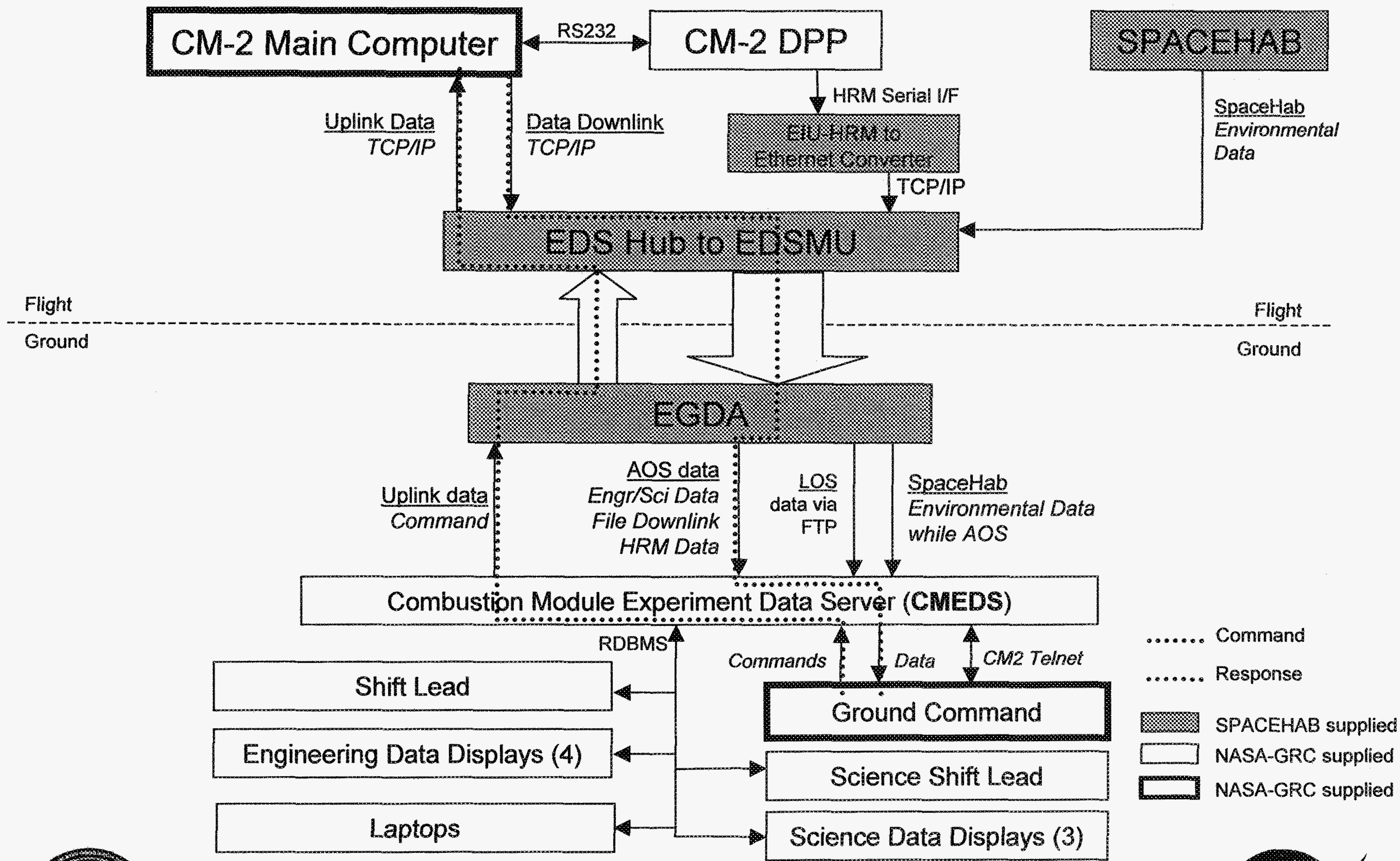
CM-2 Flight & Ground System Data Flow



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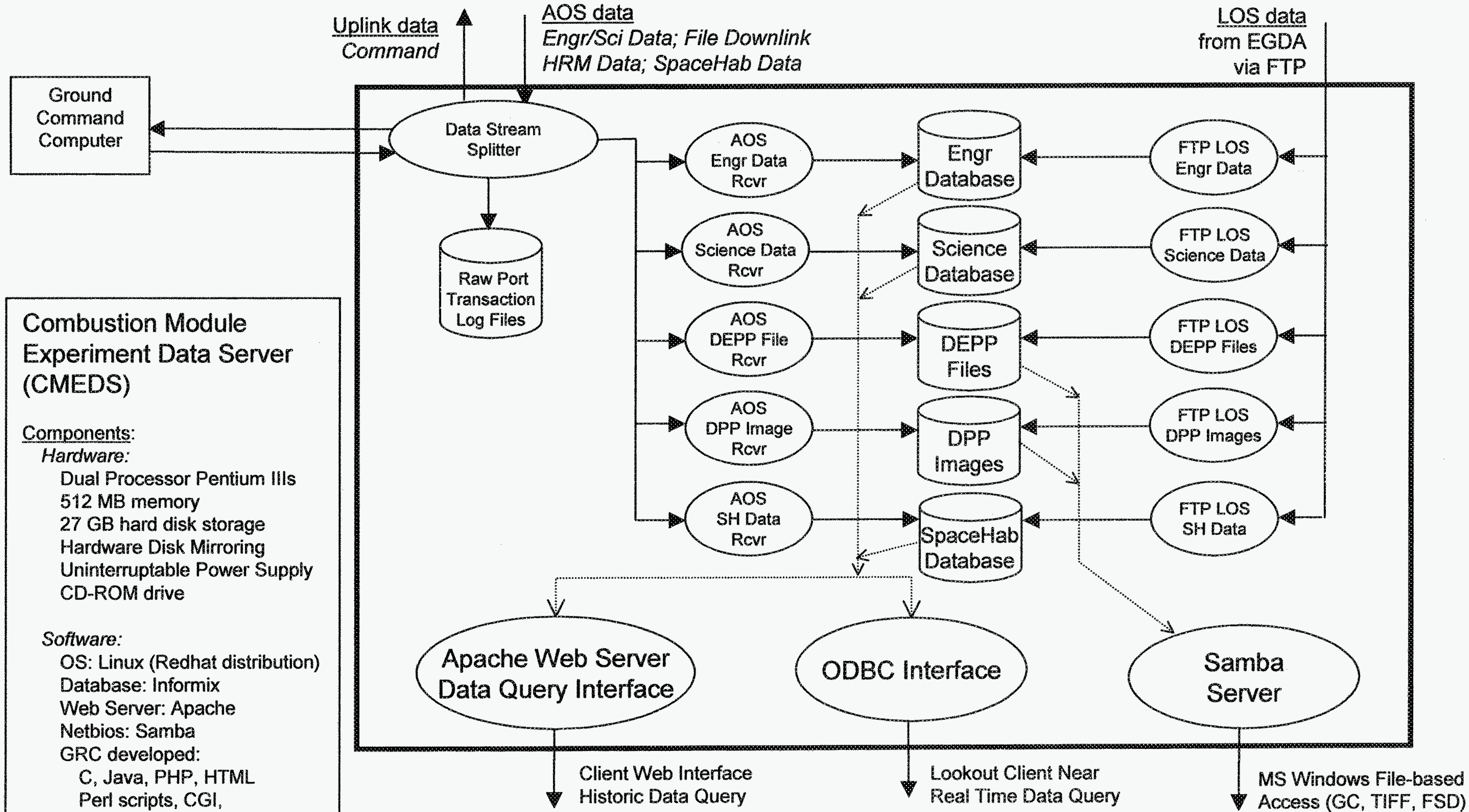
CM-2 Ground Server Data Flow



Combustion Module Experiment Data Server (CMEDS)

Components:

Hardware:

- Dual Processor Pentium IIIs
- 512 MB memory
- 27 GB hard disk storage
- Hardware Disk Mirroring
- Uninterruptable Power Supply
- CD-ROM drive

Software:

- OS: Linux (Redhat distribution)
- Database: Informix
- Web Server: Apache
- Netbios: Samba
- GRC developed:
  - C, Java, PHP, HTML
  - Perl scripts, CGI,
  - shell scripts

Author Biography

David Andrew Carek, P.E.

Mr. Carek is a senior research engineer in the Satellite Networks and Architectures Branch at the NASA Glenn Research Center. He is currently working on advanced communication system architecture concepts for the International Space Station. Prior to his current position, Mr. Carek managed flight software development for the Combustion Module-2 microgravity experiment. Mr. Carek has 15 years experience in computer systems integration and 7 years experience in flight software development and project management. He started his career at NASA performing structural analysis and developing computer-aided-engineering systems for advanced capabilities in structural analysis and design. Mr. Carek graduated magna cum laude in 1988 with a BSME from the University of Toledo, where he was selected as the "Outstanding Engineering Student of the Year" by the Ohio Society of Professional Engineers. Mr. Carek is a recipient of the "Silver Snoopy" award for outstanding efforts that contribute to the success of human space flight missions.