Telemetry Storage Systems: A Comparison of Mission Approaches

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(Not ITAR Restricted)
Overview

- Magnetospheric Multiscale (MMS)
  - Overview and Storage Approach

- Cyclone Global Navigation Satellite System (CYGNSS)
  - Overview and Storage Approach
MMS Mission

- Magnetospheric Multiscale (MMS)
  - Constellation of 4 identically spaced spacecraft in variably spaced tetrahedron (7 km to several 100 km)
  - Ground contacts must be multiplexed in time in order to retrieve data from all 4 spacecraft each day

- Objective: To discover the detailed physics of the reconnection process including its controlling factors, its spatial distribution, and its temporal behavior.
MMS Mission

- Solving Magnetospheric Acceleration, Reconnection, and Turbulence (SMART) Instrument Suite
  - Central Instrument Data Processor (CIDP)
    - SPARC Processor
    - Stores science data for the Instrument Suite
  - Instruments can collect far more data than can be sent via downlink
MMS Mission

- Highest resolution data is voluminous
  - Collect best quality data for region of interest
MMS Storage Approach - CFDP

- CCSDS File Delivery Protocol
  - CFDP is a protocol for transferring files to and from a spacecraft memory
    - Files can be transferred reliably, where it is guaranteed that all data will be delivered without error, or unreliably, where a best effort delivery capability is provided.
    - Files can be transmitted through at various speeds through different link types and through intermediate relay spacecraft.
      - Class 1 - Unreliable transfer
      - Class 2 - Reliable transfer
      - Class 3 - Unreliable transfer via one or more waypoints in series
      - Class 4 - Reliable transfer via one or more waypoints in series
    - File transfer can be initiated automatically by the onboard entity or manually by ground control.

Since we do not relay through intermediate waypoints, only Class 1 and Class 2 service are implemented on the MMS CIDP entity. In order to maximize the science data return, file transfer is initiated by the entity onboard.
Why use CFDP?

- **Downlink is a precious resource**
  - Ground contacts are limited - make the most of them
  - Lost data can mean lost opportunities for science

- **Operations costs are a significant part of the mission budget**
  - CFDP helps to automate routine data delivery operations to simplify operations, thereby providing some promise for reducing these costs

- **Standard protocol encourages interoperability**
  - Benefit realized as CFDP is adopted on more missions
MMS Storage Approach - CFDP

- **Highlights**
  - CCSDS Space Packet Protocol is underlying protocol
  - Class 2 (Reliable) with Deferred NAK
  - Class 1 (Unreliable) is backup

- **CIDP Mass Memory is Virtual Filestore**
  - No File System
  - Partitioned into 4 MB fixed-size files
  - Flash buffers managed in pools
    - In-use
    - Free
    - Held
    - Available for downlink
    - Downlink may occur while in region of interest

- **Use NASA GSFC CFDP Library**
  - Implements State Machines
  - Interfaces to User Application, Virtual Filestore and Communications System

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*Timers are used to ensure retransmission of the EOF, Nak, and Finished messages as required. The Nak message reports all missing data (including Metadata).*
MMS Storage Approach - CFDP

- **Application Interface**
  - Calls to CFDP Library
    - Set Configuration (i.e. MIB) Dynamically
    - Give Request to Library
    - Give PDU to Library
    - Control delivery rate for PDUs
      - Function invoked to send next data PDU
    - Register callbacks for Indication
  - Callbacks from Library

- **Virtual Filestore Interface**
  - Callbacks from library
    - File I/O primitives
      - fopen(), fseek(), fread(), fwrite(), feof(), fclose()
    - Other Posix primitives
      - rename(), remove(), tmpnam()

- **Communication System Interface**
  - Callbacks from Library
    - Open PDU channel
    - Channel Ready?
    - Send PDU on channel
MMS Storage Approach - CFDP

- Virtual Filestore Interface
  - Callbacks from library
    - File I/O primitives
      - fopen(): transfer file to Output Buffer and optionally perform compression
        - Set start offset to 0
        - Return corresponding buffer index
      - fread(): If first call after fopen() or fseek(), then initiate HW playback
        - Simply advance read count
      - fseek(): Set HW start offset for retries
      - fwrite(): Not allowed

- Communication System Interface
  - Callbacks from Library
    - Open PDU channel
      - Initiate HW handshaking
    - Channel Ready?
      - HW ready if SpW link is up
    - Send PDU on channel
      - Send File Directive PDUs to Data Formatter to include in VC stream
      - Ignore File Data PDUs – these are being generated by the
MMS Storage Approach - CFDP

- Use Virtual Filenames
  - Mass Memory Buffer Index + Timestamp
- Hardware forms File Data PDUs
- Software forms and responds to File Directive PDUs
- Hardware/Software Synchronization
  - Hardware provides for configuration of start and end offsets in Mass Memory Buffer
    - Aligned on segment boundaries (i.e. ~ 1 KB)
    - Once playback is initiated, HW transfers File Data PDUs until completed
      - Interrupt wakes up SW task when a number of segments have been transferred
      - SW task calls CFDP Library rate control function in a loop to match up file read pointer with those segments sent by HW
CYGNSS Mission

- Cyclone Global Navigation Satellite System (CYGNSS)
  - Constellation of 8 low-earth orbiting microsatellites that receive both direct and reflected signals from the Global Positioning System (GPS) satellites
  - Direct signals pinpoint satellite positions, while the reflected signals respond to the ocean surface roughness, which can be used to derive wind speed

Objective:
Study the relationship between ocean surface properties, moist atmospheric thermodynamics, radiation and convective dynamics, to determine how a tropical cyclone forms and strengthens.

http://clasp-research.engin.umich.edu/missions/cygnss
The 8 CYGNSS microsatellites are at an inclination of 35 degrees and are each capable of measuring 4 simultaneous reflections, resulting in 32 wind measurements per second across the globe. Ground tracks for 90 minutes (left) and a full day (right) of wind samples are shown above.
CYGNSS Storage Trade Study

- To CFDP or not to CFDP?
  - In contrast to MMS which had long contacts (1 hour / day), CYGNSS has much shorter contacts (10 minutes / two days).
  - USN does not have bandwidth to relay playback data in real-time
  - No substantial benefit to using CFDP in this case

<table>
<thead>
<tr>
<th>Considerations</th>
<th>CFDP</th>
<th>Custom Packet Replay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost to Design</td>
<td>No Impact</td>
<td>Minimal Negative Impact</td>
</tr>
<tr>
<td>Cost to Implement in FSW</td>
<td>Moderate Negative Impact</td>
<td>Moderate Negative Impact</td>
</tr>
<tr>
<td>Cost to Implement in EGSE</td>
<td>Moderate Negative Impact</td>
<td>Minimal Negative Impact</td>
</tr>
<tr>
<td>Ground System and Operations Software</td>
<td>Major Negative Impact</td>
<td>Minimal Negative Impact</td>
</tr>
<tr>
<td>FSW Size</td>
<td>Moderate Negative Impact</td>
<td>Minimal Negative Impact</td>
</tr>
<tr>
<td>FSW Processor Load</td>
<td>Moderate Negative Impact</td>
<td>Minimal Negative Impact</td>
</tr>
<tr>
<td>Downlink Rate</td>
<td>Moderate Negative Impact</td>
<td>No Impact</td>
</tr>
</tbody>
</table>
CYGNSS Storage Approach

- Hybrid Hardware/Software Implementation
  - Use CCSDS Space Packet Protocol without CFDP
  - Simple Sequential Input/Output

  **Hardware**
  - Does playback heavy lifting
    - Maximizes downlink*
    - Read back CCSDS Space Packets
    - Formats packets into frames and ultimately CADUs
    - One block at a time
      - Interrupt software when block playback complete

  **Software**
  - Does recording heavy-lifting
    - Command ERASE of Flash blocks
    - Write complete pages of Flash
    - Flash blocks only contain complete packets to facilitate hardware playback
    - Tracks bad blocks
    - Chains together consecutive blocks for playbacks

* - A hardware implementation of the CFDP protocol would be much more complex.
CYGNSS Storage Approach

- CCSDS Space Packets stored in partitions that consist of sequential blocks of Flash memory

First Flash Block
Contains a single ENG_FILL packet that is used to flush the VCDU buffer out of the hardware at the conclusion of any TLM playback

Flash Block W
ENG_STORED_NOM
Nominal Engineering
Played Back through FPGA on VC2

Flash Block X
SCC_STORED_NOM
Nominal Science (DDMs)
Played Back through FPGA on VC3

Flash Block X + 1

Flash Block Y

Flash Block Y + 1
SCC_STORED_RAW
Raw IF Science
Played Back through FPGA on VC3

Flash Block Z

Flash Block Z + 1
ENG_STORED_DIAG
Diagnostic Engineering
Played Back through FPGA on VC2

Last Flash Block
## CYGNSS Storage Approach

- **Data Structures - Flash Allocation Table (FAT)**
- **Track playback and record pointers for circular buffers**

<table>
<thead>
<tr>
<th>Engineering Stored Nominal</th>
<th>Engineering Stored Diagnostic</th>
<th>Science Stored DDM</th>
<th>Science Stored RAW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Next Block To Be Recorded uint32_t</td>
<td>Block just before Next Block to be Played Back uint32_t</td>
<td>Block Area Start Index uint32_t</td>
<td>Block Area Length uint32_t</td>
</tr>
<tr>
<td>[Block Index]</td>
<td>[Block Index]</td>
<td>[Block Index]</td>
<td>[Block Index]</td>
</tr>
<tr>
<td>[Page Number]</td>
<td>[Number of Bytes]</td>
<td>[Overwrites Allowed]</td>
<td>[Byte Counter]</td>
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<tr>
<td>Next Record Page uint32_t</td>
<td>Number of Bytes Buffered uint32_t</td>
<td>Overwrite Status uint32_t</td>
<td>Ticking Byte Counter uint32_t</td>
</tr>
</tbody>
</table>
**CYGNSS Storage Approach**

- record_blk points to the block that is to be written next.
- playback_blk+1 points to the block that is to be played back next.
- If playback_blk+1 = record_blk, then the type is EMPTY (nothing to playback).

$s = \text{size of telemetry type partition in blocks}$
Block N+1
Block N+2
Block N+3
Block N+4
Block N+5
...
Block N+s-2
Block N+s-1

s = size of telemetry type partition in blocks

record_blk points to the block that is to be written next.
playback_blk+1 points to the block that is to be played back next.
If record_blk = playback_blk, then the type is FULL (nothing to record).
**CYGNSS Storage Approach**

- **Data Structures - Flash Block Table (FBT)**
- Track number of ERASE cycles and bad blocks

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<td>[NOT-BAD / BAD]</td>
</tr>
<tr>
<td>#2</td>
<td>[Erase Count 2]</td>
<td>[NOT-BAD / BAD]</td>
</tr>
<tr>
<td>#3</td>
<td>[Erase Count 3]</td>
<td>[NOT-BAD / BAD]</td>
</tr>
<tr>
<td>#4</td>
<td>[Erase Count 4]</td>
<td>[NOT-BAD / BAD]</td>
</tr>
<tr>
<td>#5</td>
<td>[Erase Count 5]</td>
<td>[NOT-BAD / BAD]</td>
</tr>
<tr>
<td>#6</td>
<td>[Erase Count 6]</td>
<td>[NOT-BAD / BAD]</td>
</tr>
</tbody>
</table>

Size = 128 kB MRAM

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**Data Structures**

- Flash Block Table (FBT)
  - Track number of ERASE cycles and bad blocks

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**CYGNSS Storage Approach**

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Size = 128 kB MRAM
Summary

- **Magnetospheric Multiscale (MMS)**
  - Used CFDP as a front-end for a primitive file system
  - Reliable file transfer provided in the protocol
  - Worked well for daily contacts of about 1 hour

- **Cyclone Global Navigation Satellite System (CYGNSS)**
  - Used a simple sequential record/playback approach
  - Reliable file transfer not provided by the protocol but loss is tolerable
  - Expect to work well for short contacts where playback data is buffered by USN and not relayed in real-time to mission operations