Johns Hopkins
Applied Physics Laboratory

The Cubesat Assessment and Test (CAT) Program – Mission Operations Evolution

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Abstract / Agenda

- CAT Mission Overview
- Mission Integration Role
- Mission Evolution
- CAT Ground System
- Mission Operations Autonomy
  - Unattended Operations
  - SciBox Automated Mission Planning Tool
- CAT Radio Trade
- AWS Implementation
- Conclusion

This presentation discusses JHU/APL's experience building, integrating, and operating this small sat mission as well as the operational approaches planned pre-launch and those developed post-launch for the CAT mission.

Mission Overview

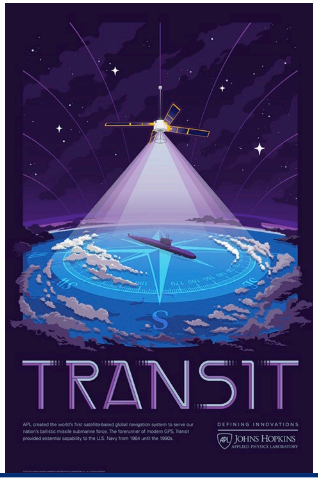
- CAT 1 and 2 Spacecraft launched from Cape Canaveral on December 5, 2018 to the ISS
- CAT spacecraft were deployed on January 31, 2019
- CAT naturally de-orbited on April 13, 2021
- The CAT flight demonstration mission was very successful operating two satellites in low earth orbit (LEO) for 2 years and 2 months from deployment to deorbit
- The mission completed over 800 payload measurements
- A flexible, practical and cost-effective technical approach was implemented that leveraged the heritage of current and legacy APL missions
- Successful implementation of cost-effective automated processes (e.g. unattended contact operations, SciBox mission planning software)
- Post-launch integration of a commercial ground station via Amazon Web Services (AWS)
- Successful orbit management of satellites demonstrated using differential drag maneuvers to maintain a close (< 150 km) relative satellite separation distance without the use of propulsion subsystem.
- APL maintained nominal mission operations with COVID-19 restrictions without impact to payload operations.

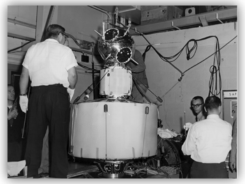
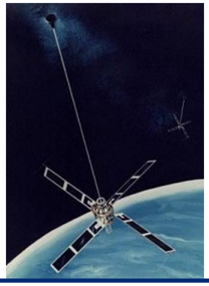
Mission Integration Role - Background

- JHU/APL traces its origins to the post World War II high altitude research using V-2 rockets
- During the first few decades of the Space Age, APL's work expanded to include signification contributions to the civilian space program as well as the country's national security

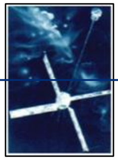
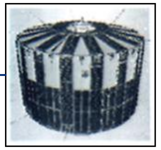
Early APL Smallsats - Transit

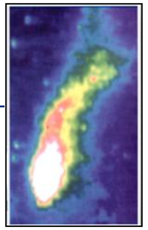
- First satellite navigation system to be used operationally
- The Transit satellite system, sponsored by the Navy and developed jointly by DARPA and APL under the leadership of Dr. Richard Kershner at Johns Hopkins, was the first satellite-based geopositioning system
- First Launch 1959
- Last Launch 1988

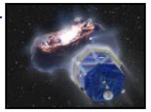



1958 Satellite Navigation System
1961 Nuclear-powered spacecraft
1963 Gravity gradient stabilization
1967 Color picture of the full Earth
1972 Drag-compensated satellite
1975 Pulsed plasma thrusters
1982 Autonomous satellite navigation with GPS
1984 Artificial Comet
1986 Intercept of a thrusting target in space
1988 Autonomous target acquisition and Track
1996 Near Earth Asteroid Rendezvous (NEAR)
1996 First Hyperspectral Imager in Space (MSX)
1996 Invention of Polymer Battery
2001 Landing on an Asteroid (NEAR)
2002 Two-Way Non-coherent Doppler Tracking (CONTOUR)
2003 Re-Configurable Self-Repairing Processor (FEDSAT)
2004 First orbital Mercury exploration mission launched
2006 First mission to Pluto launched (New Horizons)
2011 First Mercury Orbiter
2015 First Pluto flyby
2018 Closest mission to the Sun launches

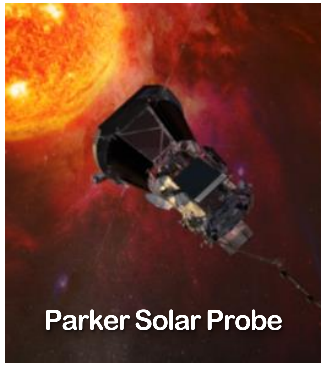


APL Space Exploration Sector

- Long experience in complete end-to-end mission design.
- >70 spacecraft launched
- Over 300 sensors and payloads delivered
- Short time to space
  - Tight requirements process
  - Disciplined development
  - Unparalleled cost/schedule performance
- >150 Modeling and Simulation & Analysis and Science Projects in progress continuously
- Trusted-agent studies in support of NASA, NOAA, and DoD
- Status as a UARC enhances effective collaborations with industry and government
- Tailored product assurance process ensures small satellite mission success.

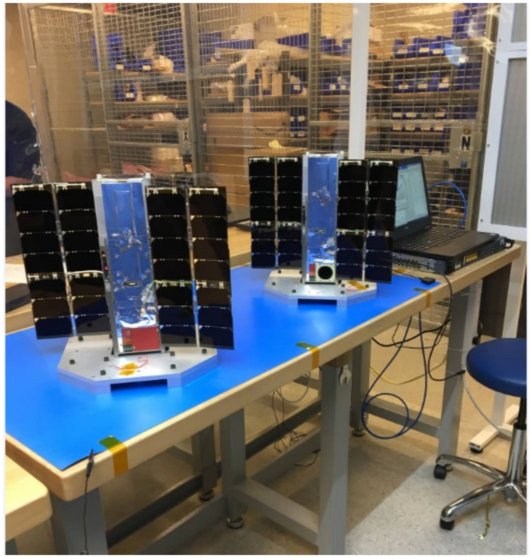
Innovative and Cost-Effective End-to-End Space Missions



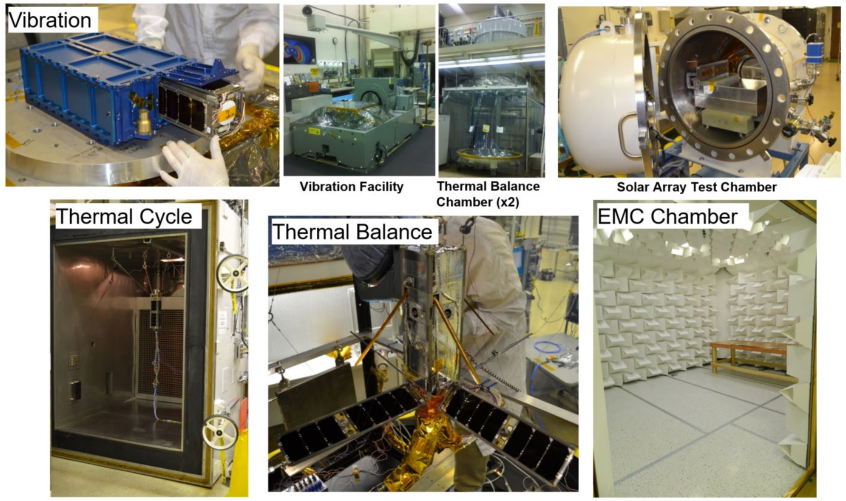
Comprehensive support of civil and national security programs

CAT Mission Integration Role

- Mission Integrator Role
  - Leverage mission partners in role of Mission Integrator
  - Perform trades throughout the lifecycle to determine to leverage industry advancements
  - Lead the mission formulation from an initial top level set of objectives, requirements, and goals to post-launch operations
  - Implement CONOPs that can be matured through modeling, simulation and analysis (MS&A)
  - Executes make/buy trades necessary to design and implement, or procure the spacecraft bus and other required hardware
  - Maintain the necessary level of oversight throughout the design and development phases
  - Environmental and performance testing of payload and spacecraft hardware
  - Lead I&T of the spacecraft bus and payload
- APL utilized this MI role on CAT
  - Assessed industry supplied spacecraft buses
  - Utilized an industry bus achieving cost savings while still proving an overall mission within the given risk posture
  - Payload integration and spacecraft I&T in house a APL leveraging its extensive I&T experience to identify risk reduction activities and identify potential mission ending faults
- Risk mitigation activities included
  - Testing the spacecraft and payload engineering models with the actual ground station
  - Develop mission simulations and rehearsals for launch and early operation events
  - Use APL's proven smallsat environmental test facilities with experienced personnel
- CAT required a low cost mission operations approach
  - Unattended operations and automated mission planning were a necessity



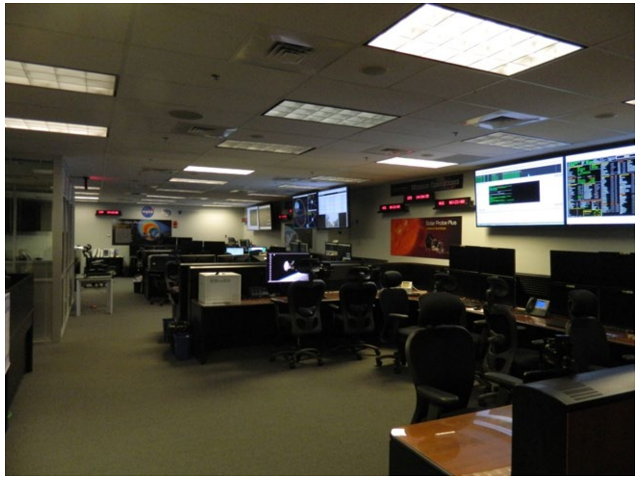
CAT Satellite Integration

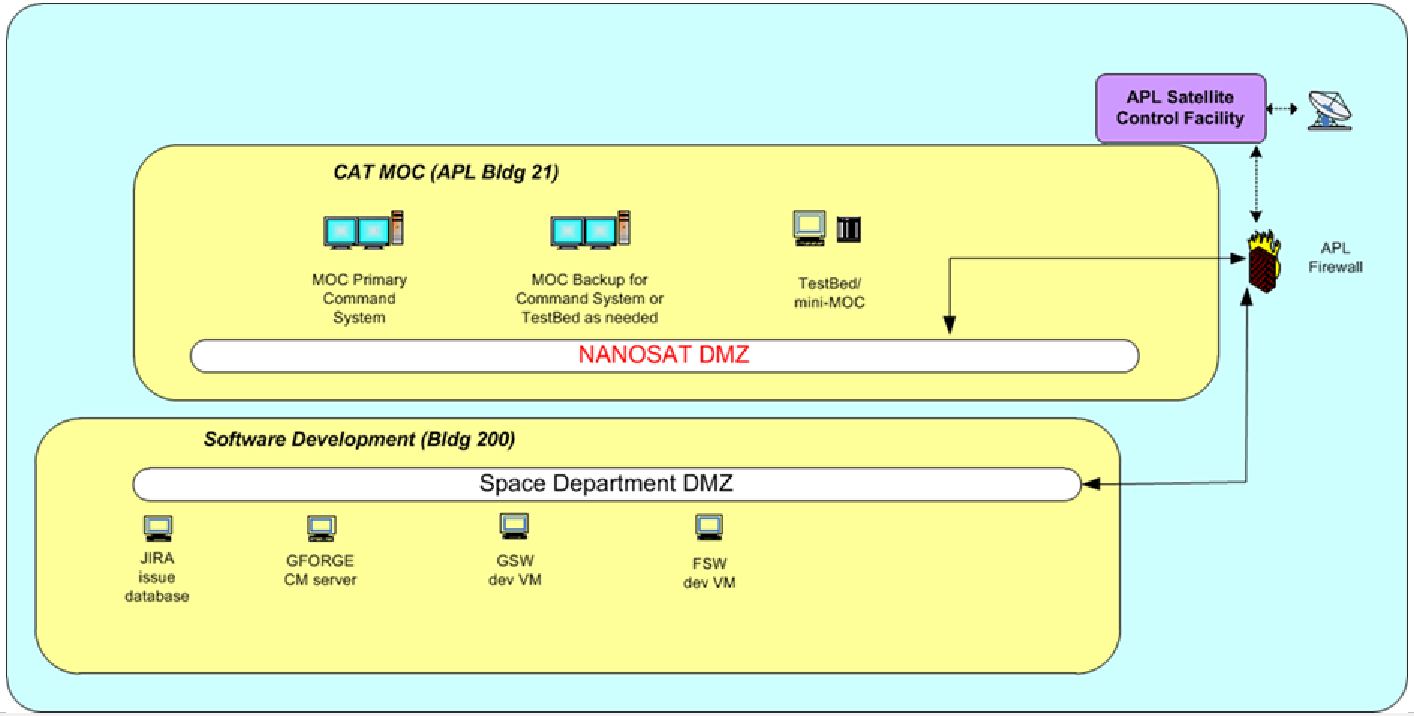


APL Smallsat Environmental Testing

CAT Ground System

- State-of the Art Multi Mission Operations Center (M2MOC)
- Integrates L3's InControl Command Telemetry System
- Key features of the MOC include CCSDS and Space Link Extension Compliance, Multiple Firewalls, UPS and Generator Backup and adherence to NASA IONet Security Regulations
- Unattended Operations runs on NanoSat DMZ and sends out emails and/or text messages





Mission Operations Autonomy

- Necessary for CAT
  - Overall cost constraint where a full mission operations team could not be afforded
  - Relatively short contact passes each spacecraft saw per day
    - Only 400 km altitude
    - Average contact time 6 minutes three times a day per spacecraft
    - Little time for command, telemetry review, and adjustments
  - Frequent event checks and fault modes for a low cost risk tolerant mission
- Mission Autonomy was executed by a combination of Unattended Operations and the implementation of our APL Automated Mission Planning Tool called SciBox

Unattended Operations

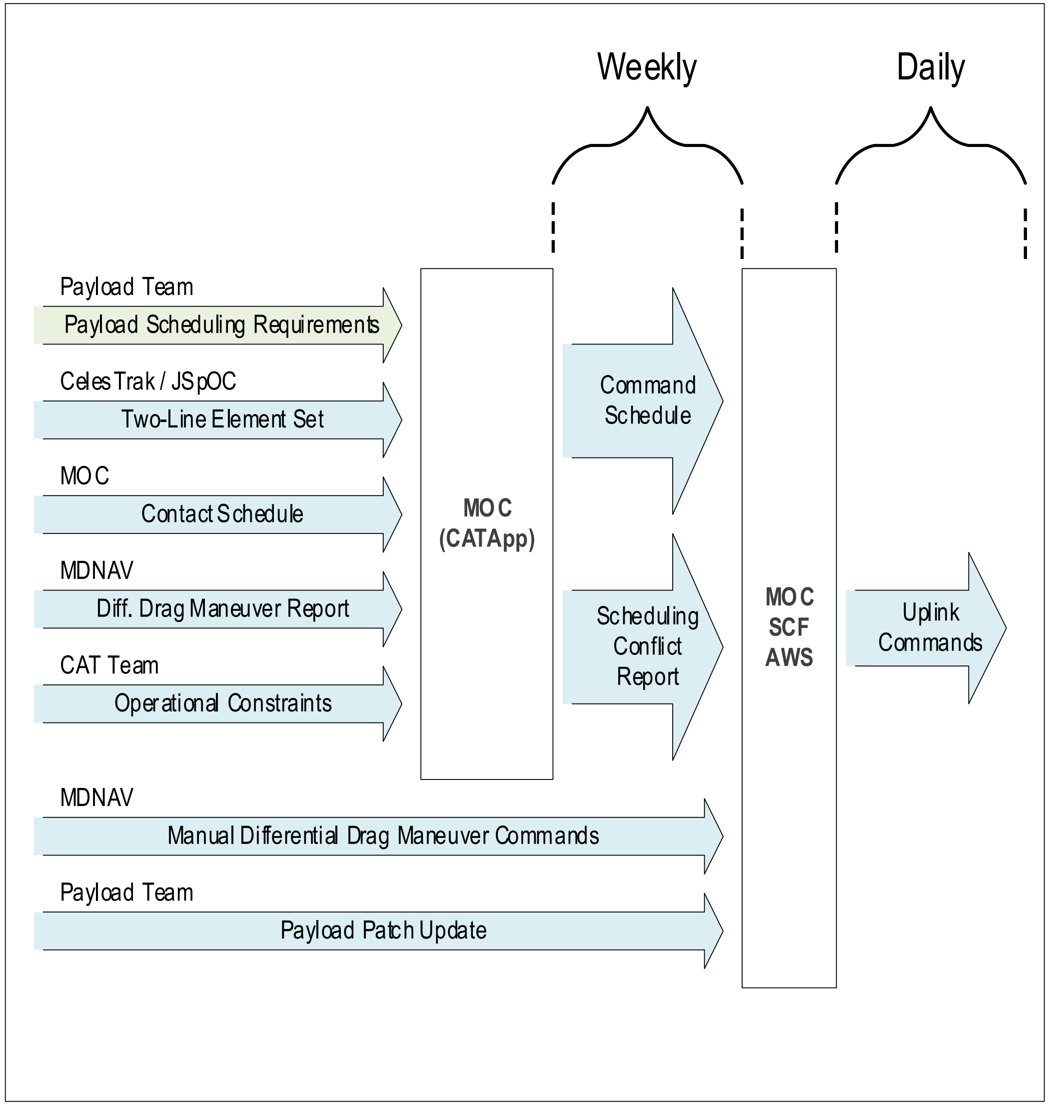
- Unattended Operations was executed with a combination of validated scripts written using the InControl Ground Software.
- Unattended Operations were used to perform routine functions such as configuring the ground station prior to a contact and executing a developed standard template of operations
- Unattended Operations Executed

For Each Contact:	During Each Contact:	Between Each Contact:
• RF link verified • Time tag command loads uplinked • Recorder playback commanded • Health & safety checks performed	• Determine data to be downlinked • Stop the default playback • Command new playback with the goals for the current pass.	• Process recorder data • Dump data to the ground fed back to the MOC • Retransmit data on the next contact if necessary

- The Health & Safety checks performed during each contact
  - Telemetry checked for out-of-limit and expected-state conditions
  - Status report emailed to the team (command activities, telemetry out-of-limit conditions and unexpected states)
  - Page team members for any anomalies
  - Determined if routine or recovery operations were performed
- Unattended Recovery Operations
  - Initiated if there was no telemetry at AOS.
  - In the event of a negative acquisition, Ground would attempt a downlink, and reboot radio components as necessary
  - The CAT spacecraft frequently went into safe mode. Therefore, unattended operations expanded to recover from a sun pointing attitude and return to normal operations.
  - After a downlink was established, spacecraft time and ephemeris were loaded and spacecraft event checks cleared.
  - Time tag loads were resumed from the current time.

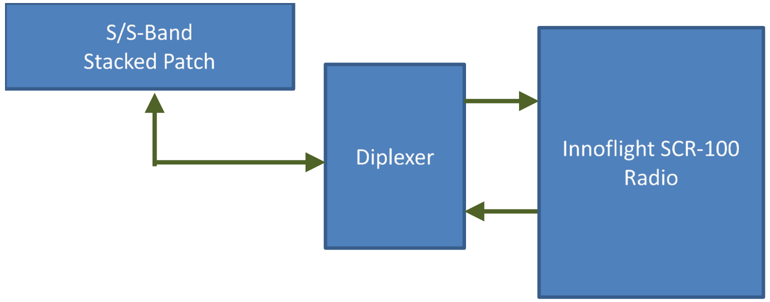
SciBox Automated Mission Planning Tool

- CATApp is a software program developed by APL for the planning and scheduling of satellite operations
- CATApp is an instantiation of SciBox, which is a larger software platform used across other APL missions
- For the CAT mission, CATApp was used to generate a deconflicted command schedule for each satellite on a weekly basis.
- The Mission Operations Team implemented CATApp in the following sequence:
  - Schedule South Atlantic Anomaly (SAA) events
  - Schedule payload collect events
  - Schedule ground station contacts
  - Schedule eclipse maximum differential drag maneuvers
  - Schedule eclipse minimum differential drag maneuvers
- In addition to scheduling activities, CATApp also enforced operational constraints:
  - Prevent scheduling of a payload collect within 6 hours of each other (≈ 4 orbits) for power and thermal recovery
  - Prevent scheduling of a ground station contact when ISS, NOAA-20 or SNPP satellites are in view of the SCF or AWS ground stations
- Allowed updates to operational sequences and configurations throughout mission such as:
  - Updated Payload Command Sequences
  - Adjusted timing and constraints of CMD sequences
  - Added new scheduleable ground stations for AWS



CAT Radio

- The CAT RF subsystem has two primary functions: provide spacecraft command capability and provide spacecraft telemetry and payload data return.
- Early trade to replace the bus provided 9600 bps TT&C UHF radio with a high TRL, S-Band COTS solution.
  - The result of that trade was the Innoflight SCR 100 radio.
  - The Innoflight radio provides a Software-defined Compact Radio (SCR), full duplex operations, supports multiple modulation/coding and variable data rates, and provides a variable output power of 20 mW to 1.8W
  - An integral diplexer facilitates the interface between the antenna and radio

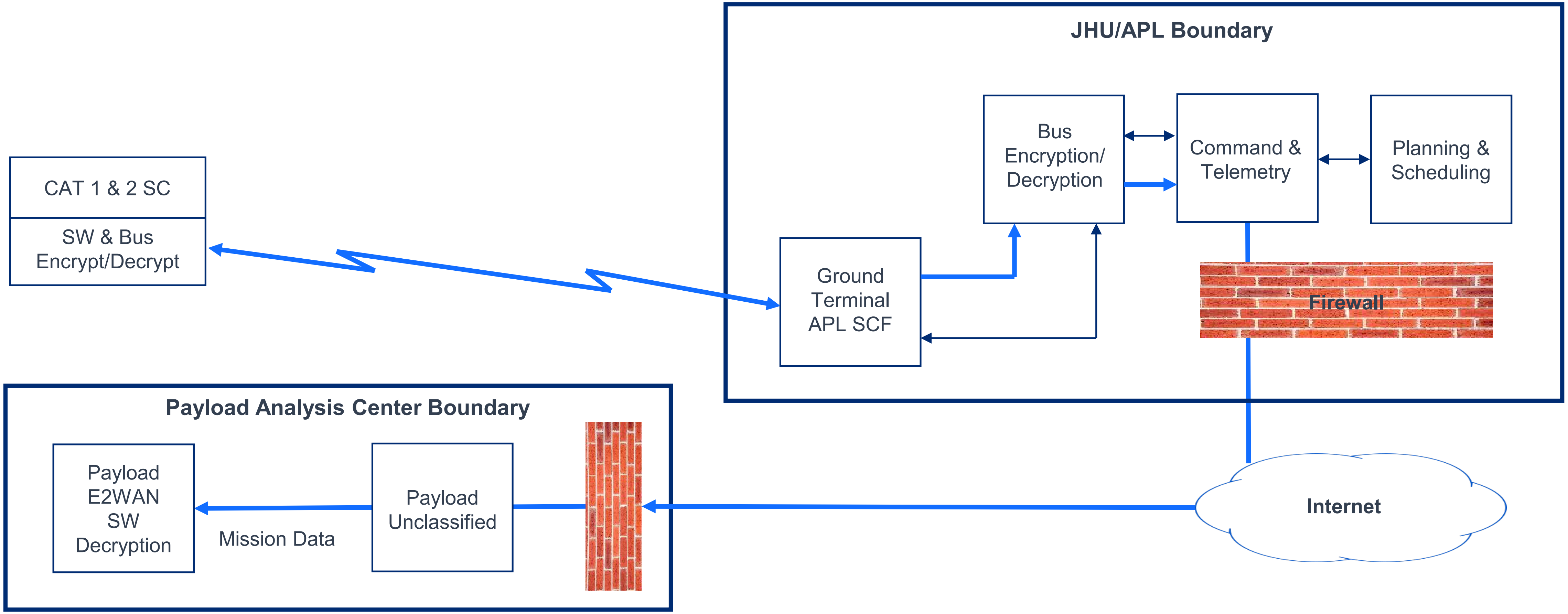


- The CAT mission encryption/decryption feature is provided by the radio.
- The encryption module interfaces to the spacecraft's C&DH and handles both radio commands and data on a single serial port.
- The encryption module encrypts the data using AES-256 in Galois/Counter Mode GCM mode and adds High Level Data Link Control (HDLC) encoding.
- The data is then passed to the S-Band transmitter for downlink The uplink process is complimentary to the downlink.
- The uplink signal is received via either antenna to the diplexer where they are routed to the receiver.
- An AntDevCo S-band stacked patch antenna on the space vehicle provides a single nadir-facing antenna for TT&C.

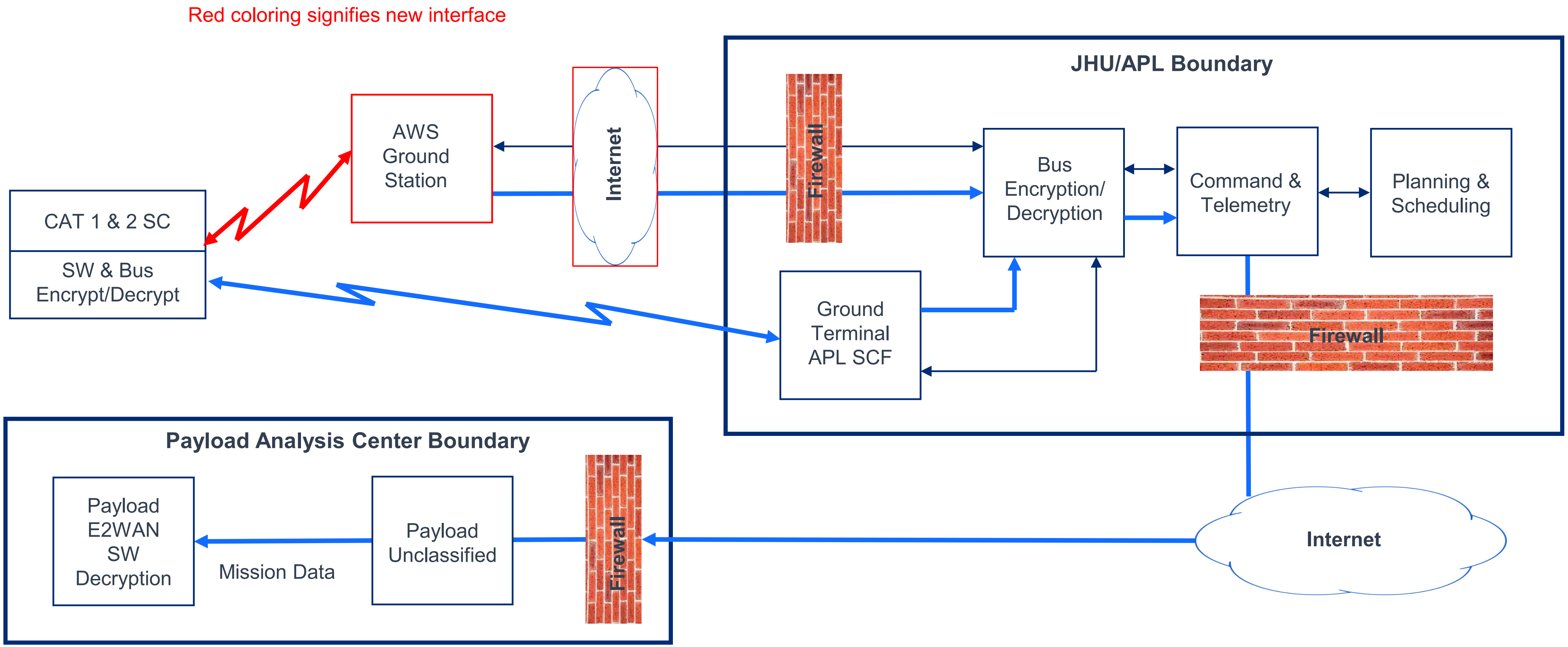
AWS Implementation

- After the initial mission prototype demonstration requirements were satisfied, APL wanted to extend the mission to continue payload collection events and increase data return.
- In addition, the satellites were naturally de-orbiting so there was limited time to collect data.
- Additional contacts were desired to increase the amount of satellite contacts and data thru-put.
- Amazon Web Services Ground Station Network was selected and implemented into the program.
- In FY20, APL funded an IRAD task evaluating the utilization of AWS.
- Several shadow passes were captured with AWS using APL's TIMED spacecraft.
- Key elements such as data security in commercial facilities, integration with APL ground systems, and integration with other ground and processing systems were successfully investigated.
- This IRAD led to an easier implementation of using AWS for an already flying mission in CAT.

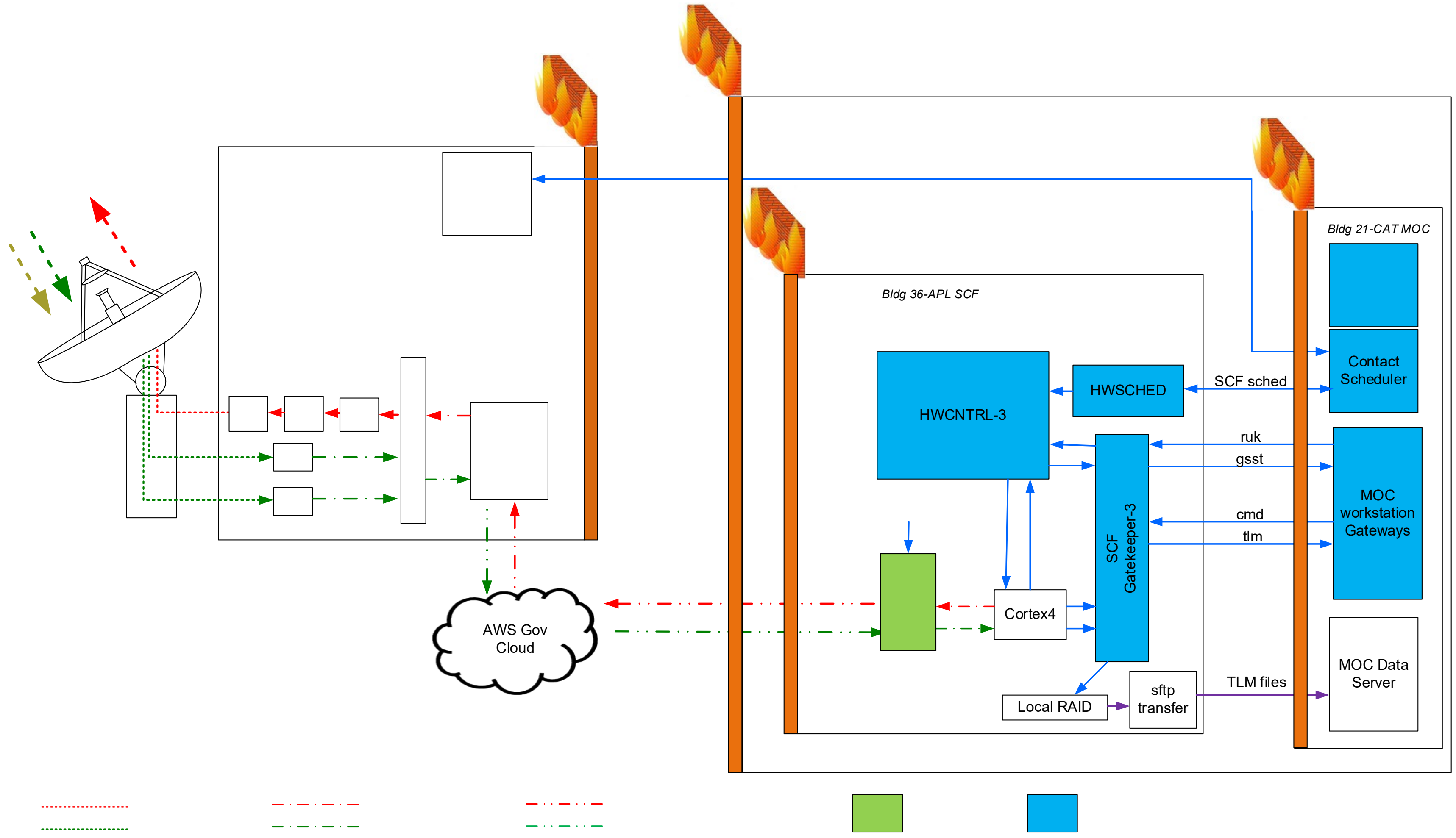
CAT End to End Architecture



CAT Augmented End to End Architecture



CAT Data Flow Approach



- Minimize impact to existing systems and integrate without disrupting current mission operations
- Use a digitized IF transport between AWS and the APL SCF thus integrating the AWS aperture into the existing signal chain at the SCF
- Downlink / Uplink:
  - AWS SpectralNet Device to Spectral Net located in SCF
  - Downstream telemetry path utilizes the existing SCF and CAT MOC interfaces and infrastructure for processing the telemetry data
- Ground Station Control and Status:
  - MOPS sends commands to control the Cortex, using the existing RUK interface.
- Ground Station Scheduling:
  - MOPs will schedule both the AWS ground station and the equipment in the SCF (i.e. Cortex, Gatekeeper) for AWS passes.

CAT Ground Station Locations

- The Dublin, Ireland AWS Ground Station was selected as it benefited the CAT mission being at a good geographic diverse location from the APL dish in Laurel, Maryland
- Additional locations were being considered to further increase data return.
- Those locations were under NTIA license review, but the satellites eventually de-orbited before the approvals were granted.

Conclusion

- The CAT mission was a very successful mission from the mission integration approach to providing program necessary autonomy in the mission operations planning and execution cycle
- Many challenges were experienced and the team evolved from launch and early orbits to early mission prototype demonstration to being able to extend the mission with valued payload data implementing mission autonomy with mission planning and unattended operations
- AWS ground network was put in place with a secure end to end encrypt/decrypt data flow process proven
- The CAT mission design and objective was for 6 months life. The total mission operated a little more than two years with a full two years of data collection events.
- APL is ready to implement lessons learned and similar approaches from our mission operations evolution with new partners and sponsor missions

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