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The Cubesat Assessment and Test (CAT) Program - Missions Operations Evolution

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ABSTRACT

On January 31, 2019, the CubeSat Assessment and Test (CAT) mission deployed from the International Space Station (ISS). The primary objective of the CAT mission is to use two COTS 3U spacecraft to support a communications experiment. CAT completed its primary mission success objectives in two months and continues to collect mission data two years post-launch. After meeting the mission objectives, the focus shifted to increasing data return from the payloads on the two spacecraft with the CAT team working to evolve the mission to continue to maximize its payload data return.

During its initial conception and design, the team at The Johns Hopkins University Applied Physics Laboratory (JHU/APL), along with the spacecraft provider, Blue Canyon Technologies (BCT) have performed a wide range of tasks to increase operational availability and provide more operational data. Early activities included APL management and oversight of the development of the two 3U spacecraft. During this period, APL selected the Innoflight SCR-100 radio to be used on the standard BCT XB1 bus to provide increased robustness, uplink and downlink hardware encryption, and an increased (2Mbps) downlink data rate. Early engineering choices included the decision to transition from the COSMOS-based BCT ground control system to the APL L3 InControl ground system. This provided the mission with a wealth of automated tools used by all APL-led operations, including an APL-developed automated planning and commanding technology called SciBox, as well as heritage ground scripts for "lights-out" operations via the APL Satellite Communications Facility (SCF). Post-deployment from the ISS, autonomous operations using both on-board functionality as well as autonomous ground operations, allowed the CAT operations team to continue to optimize data return by maximizing spacecraft and ground system "down time". Most recently, Amazon Web Services (AWS) was used to augment the number of ground entry points to provide addition operational data and a new end to end capability with the usage of the AWS Cloud Data Platform. This paper 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

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 combined that were used to enhance the nation's space-domain capabilities in partnership with US industry. The mission implemented a flexible, practical and cost-effective technical approach that leveraged the heritage of current and legacy APL missions, and the highly experienced talent of APL staff. Some of the key mission highlights are the 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), and orbit management of multiple satellites using differential drag maneuvers to maintain a close (< 150 km, or 20 seconds) relative satellite separation distance without the use of GPS receivers nor propulsion subsystem. APL also maintained nominal mission operations with COVID-19 restrictions without impact to payload operations. Figure 1 is a highlight picture captured by the crew of the International Space Station (ISS) as both satellites simultaneously deployed from the ISS on January 31st, 2019.

Figure 1: ISS Satellite Deployment

MISSION INTEGRATION ROLE

The Johns Hopkins University Applied Physics Laboratory (APL) Space Exploration Sector (SES) 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 significant contributions to the civilian space program as well as the country's national security. Over APL's 75+ year history, the sector has launched over 70 spacecraft (many of which meet the definition of a small sat) and over 300 instruments and sensors. While APL prides itself on full lifecycle, end-to-end mission systems, space exploration continues to evolve with new industry players entering the field every day.

APL's SES continues adapting its strategy to stay on the leading edge of technology by utilizing the vast experience gained through over 75+ years of involvement in space programs while leveraging industry partnerships. To this end, APL has developed the role of "Mission Integrator" (MI) to provide a number of benefits across the lifecycle of our cost and schedule-constrained small sat programs. A key role of the MI is to perform trades throughout the lifecycle to determine when to leverage industry advancements (i.e., to keep costs lower or to meet schedule) versus when APL needs to take a larger role in a project with direct development of more advanced flight or ground elements. The MI role leads the mission formulation from an initial top level set of objectives, requirements and goals to post-launch operations. The initial objectives, requirements, and goals are used to develop a Concept of Operations (ConOps) that can be matured through modeling, simulation and analysis (MS&A). Once the initial ConOps is developed, the MI executes the make/buy trades necessary to design and implement, or procure the spacecraft bus and other required hardware. The MI maintains the necessary level of oversight throughout the design and development phases, as well as the environmental and performance testing of subsystem payload and spacecraft hardware. The MI may also lead the integration and testing of the spacecraft bus and payload (ideally using the mission operations facility and tools that will be used post launch), as well as perform post-launch check-outs, test and evaluation campaigns, and mission operations through disposal.

APL utilized the MI role on the CubeSat Assessment and Test (CAT) demonstration mission with many benefits and lessons learned identified. For the CAT mission, APL performed a wide range of tasks as MI, including an initial assessment of industry-supplied spacecraft buses, management and oversight of the development of two 3U spacecraft provided by Blue Canyon Technologies (BCT), system integration and test of the payload and the spacecraft bus, and mission operations using an automated planning and commanding technology.

CAT received authority to proceed in the fall of 2016 with the first major task being the assessment of industry-supplied spacecraft buses. APL interacted with several smallsat providers at the time including many new industry providers which had focused on process improvements and quality – making it possible for APL to utilize an industry bus achieving cost savings while still proving an overall mission within the risk posture.

The determination was made to keep mission and spacecraft integration at APL to enhance a relatively new payload provider with a complex/sensitive RF sensor and (at the time) a fairly new SC provider with limited flight experience. APL leveraged its extensive I&T experience to identify risk reduction activities and identify potential mission-ending faults on both the SC and Payload.

Such risk mitigation activities during I&T consisted of testing the spacecraft and payload engineering models with the actual ground station on APL's campus. Using the integrated bus and payload EM, the mission operations team was able to develop mission simulations and rehearsals for launch and early operation events. Another risk mitigation was the use of APL's proven smallsat environment test facilities with the accompanying experienced personnel. APL had recently built, tested, delivered and flown a successful pair of 3U smallsats (ORS Tech 1 and ORS Tech 2) for the Multi Mission Bus Demonstration (MBD) mission.

Finally, the CAT mission was required to support a low cost mission operations approach. A traditional fully staffed Spacecraft Mission Operations team was not possible given the cost constraints making automation and unattended operations a necessity. The unattended operations scripts were written in the ground software for rapid turn-around for fault and event check recovery given the short contact times. This level of autonomy is described later in this paper.

CAT GROUND SYSTEM

The CAT mission used APL's state-of-the-art Multi-Mission Mission Operations Center (M2MOC). The MOC integrates L3's InControl command and telemetry system with heritage planning software as part of the APL Mission Independent Ground System (MIGS) architecture. Key features of the MOC include CCSDS and Space Link Extension compliance, multiple firewalls, uninterruptable power sources and generator backup, and adherence to NASA IONet security regulations.

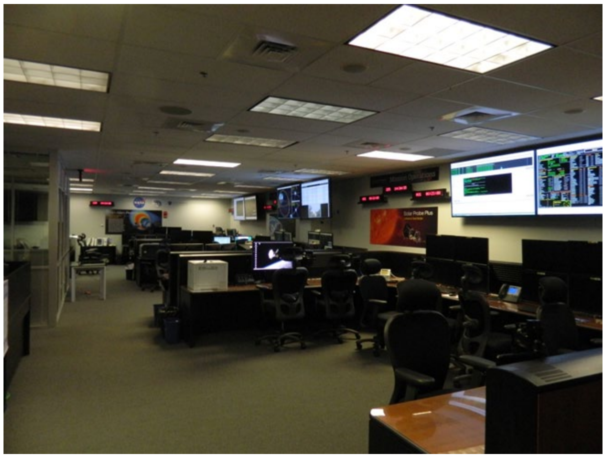

Figure 2: CAT Mission Operations Center

A block diagram of the CAT MOC Ground Architecture is shown in Figure 3.

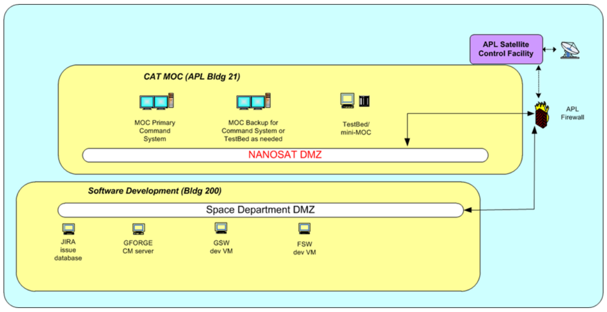

Figure 3: MOC Ground Architecture Diagram

The CAT Ground System components reside on the NanoSat DMZ, a network designed for CubeSats. There is a direct connection between the CAT MOC and the APL Satellite Communications Facility (SCF) controlling the APL18 meter antenna. Mission operations team members can remotely log onto the clients on the NanoSat DMZ and perform their daily tasks. The Unattended Operations can also run on the NanoSat DMZ and send out emails and/or text messages as needed to alert the Mission operations team of issues.

MISSION OPERATIONS AUTONOMY

Mission Operations Autonomy was necessary for CAT to support the relatively short contact passes each spacecraft sees per day, the frequent event checks and fault modes for a low cost risk tolerant mission, and the overall cost constraint where a full mission operations team could not be afforded. The mission autonomy was executed by a combination of Unattended Operations and the implementation of our APL Automated Mission Planning Tool called SciBox. Being at only a 400 km altitude, the average contact time per spacecraft was only about 6 minutes three times a day per spacecraft, so there was little time for command, telemetry review, and adjustments.

Unattended Operations

Unattended Operations was executed with a combination of validated scripts written using the InControl Ground Software.

MOC unattended operations were used to perform routine functions such as configuring the ground station prior to a contact and executing a standard template of operations. For each contact the RF link was verified, time tag command loads uplinked, a recorder playback commanded, and health & safety checks performed.

The CAT data recorder posed some challenges to mission operations. Due to uncertainties from orbit drag, uncertainties from the ground system acquisition, and the large volume of recorded data the MOC was not able to use time tagged commands to manage the recorder. Real time systems needed to determine the data to be played back for each contact. During each contact, MOC unattended operations determined the data to be downlinked, stopped the default playback and commanded a new one with the goals for the current pass.

Between passes, recorder data was processed and the amount of data successfully dumped to the ground was fed back to the MOC for closed-loop operations. Data could be retransmitted even on the next contact if necessary.

Health & Safety checks were performed during each contact. Telemetry was checked for out-of-limit and expected-state conditions. Following each contact a status report was emailed to the team which included a summary of command activities, telemetry out-of-limit conditions and unexpected states, as well as the status at AOS and LOS for subsystems that might be reconfigured by unattended operations. Following the contact the team would be also paged for anomalies. Health & Safety checks determined if routine operations were to be performed or if recovery operations were to be performed. Recovery operations were initiated if there was no telemetry at AOS. In the event of a negative acquisition the ground would attempt a downlink, and reboot radio components as necessary.

The CAT spacecraft frequently went into safe mode, and unattended operations were expanded to recover from a sun pointing attitude and return to normal operations. After a downlink was established the spacecraft time and ephemeris were loaded, heaters and other subsystems recovered, the transition out of sun pointing mode accomplished, and spacecraft event checks cleared. Time tag loads were resumed from the current time. No updates to recorder operations were required however, since all recorder dumps were determined in real time.

CATApp

In addition to Unattended Operations, an automated mission planning tool was implemented. 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, including TIMED and MESSENGER. For the CAT mission, CATApp was used to generate a deconflicted command schedule for each satellite on a weekly basis. Figure 4 provides the input and output data flow for CATApp. The Mission Operations Team implemented CATApp in the following sequence:

1) Schedule South Atlantic Anomaly (SAA) events
    a. Calculated SAA crossings based on TLE propagation and SAA zone definition
    b. Powered off payload and GPS receiver
    c. Protected sensitive components from radiation effects
2) Schedule payload collect events
    a. Imported Payload Scheduling Requirements (PSR) provided by Payload Team
    b. Executed payload collect sequence
3) Schedule ground station contacts
    a. Imported confirmed contact schedule provided by Mission Operations Team
    b. Executed ground station contact sequence
4) Schedule eclipse maximum differential drag maneuvers
    a. Imported differential drag maneuver report provided by MDNAV Team
    b. Executed maximum differential drag maneuvers during eclipse periods
5) Schedule eclipse minimum differential drag maneuvers
    a. Calculated eclipse crossings based on TLE propagation and eclipse prediction
    b. Executed minimum differential drag maneuvers during eclipse periods

In addition to scheduling activities, CATApp also enforced operational constraints:

1) Prevent scheduling of a payload collect within 6 hours of each other (≈ 4 orbits)
    a. Allowed for power and thermal recovery
2) Prevent scheduling of a ground station contact when ISS, NOAA-20 or SNPP satellites are in view of the SCF or AWS ground stations
    a. Protected high priority assets from potential RF interference
    b. Restricted for uplink only, therefore, downlink could continue, if needed

CATApp also allowed updates to operational sequences and configurations throughout mission:

1) Adjusted timing and constraints of command sequences for payload collects, SAA crossings, differential drag maneuvers, etc.
    a. Some adjustments allowed for more collect opportunities
2) Reconfigured attitude definition for minimum differential drag maneuver
3) Added new payload command sequence to allow the packetization and transfer process to be deferred to another time after a collect when there is conflict with an SAA crossing
    a. Created more collect opportunities
4) Added new attitude and site definitions for payload collects
    a. Provided more scheduling flexibility for payload collects
5) Added new schedulable ground stations for AWS
6) Added new payload configuration fields for a payload collect (e.g. priority, transfer rate)
7) Added feature to offset payload collect start times by comparing the TLE used for payload collect planning and the current TLE used for generating satellite commands
    a. Implemented towards end-of-mission when JSpOC TLEs were less accurate due to decreasing spacecraft altitude.

Mission operations implemented CATApp on a weekly basis. Towards the last few months of the mission prior to deorbit, mission operations implemented CATApp two to three times a week to ensure accurate timetag commands. Changes to CATApp followed a streamlined engineering change process that was implemented by a software engineer and verified by the systems lead, and relevant affected stakeholders, prior to flight implementation. The team also implemented a simple software configuration management process that tracked changes and allowed for reversion to a previous state.

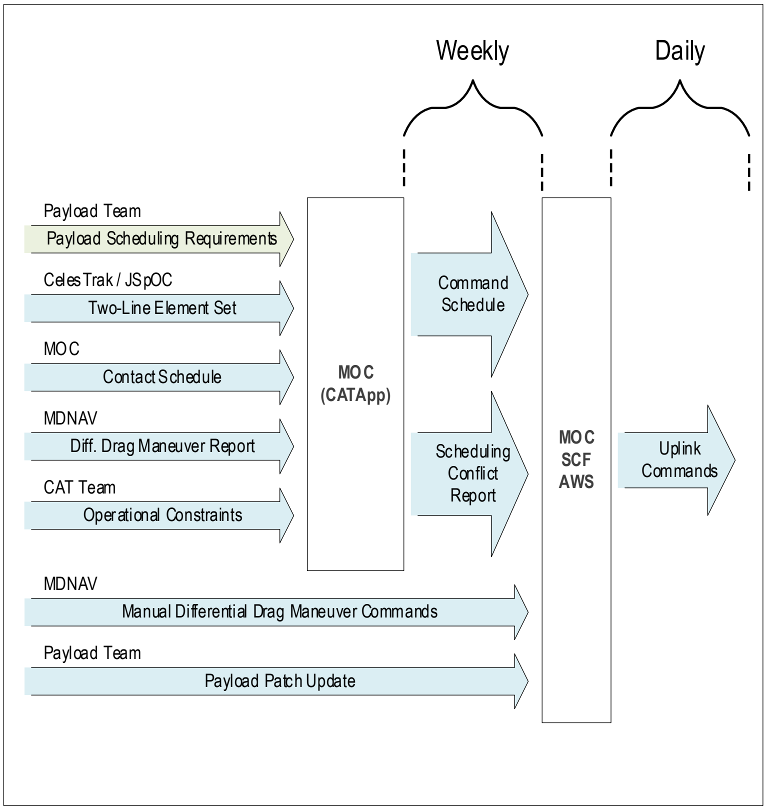

Figure 4: CATApp Data Flow

Data Flow

Early changes in the ground system software were made to accommodate the Innoflight SCR-100 radio. This required ground software updates to include “bit stuffing”, NRZ-M encoding and randomization for both test and operations. The ground crypto software, interfacing with the radio crypto described in a later section, runs on the primary production machine located in the CAT MOC. Two integration and test machines are available to serve as backups to the primary machine and were utilized in the event of a system failure on the primary machine.

The program level data flows are shown in Figure 5.

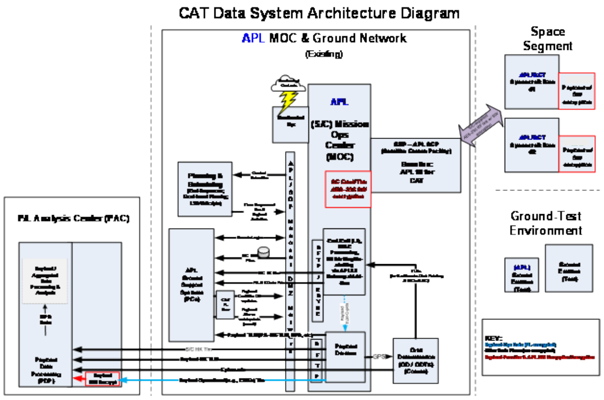

Figure 5: CAT Program Data Flow Diagram

The data flow between the space segment and the APL Satellite Communications Facility (SCF), labeled "Radio-supplied AES-256 RF link" in Figure 5, is 10 Kbps uplink ad 2Mbps operational downlink. The downlink also has an emergency rate of 100 Kbps.

Once data is received into the SCF the AES-256 encryption applied by the spacecraft radio is de-crypted and the data is passed to the APL Mission Operations Center (MOC) where the spacecraft telemetry and payload housekeeping telemetry is viewed by the operations team and stored for review and trending. The payload operational data which is still encrypted by the payload encryption process is made available via SFTP to the Payload Analysis Center (PAC) along with spacecraft and payload housekeeping data.

Commands to the spacecraft are generated in the MOC, encrypted there by the ground software and sent to the SCF for transmission to the spacecraft. At the spacecraft the radio decrypts the uplinked command, and passes the un-encrypted data to the spacecraft and/or payload.

RADIO

The CAT RF subsystem has two primary functions: provide spacecraft command capability and provide spacecraft telemetry and payload data return. Figure 5 is a block diagram of the CAT RF subsystem. An early trade for CAT was to replace the 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 GCM mode and adds HDLC encoding. The data is then passed to the S-Band transmitter, where concatenated forward error correction is added to the data and then modulated using Offset-QPSK on an S-Band downlink. Last, the modulated RF signal is fed into a diplexer where it is combined with the uplink band and split equally to two antenna ports. 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. The receiver demodulates the PCM-FM/FSK/GMSK/GFSK modulation and passes it to the encryption module where it is decrypted, authenticated, and passed to the C&DH. An AntDevCo S/S-band stacked patch antenna on the space vehicle provides a single nadir-facing antenna for TT&C.

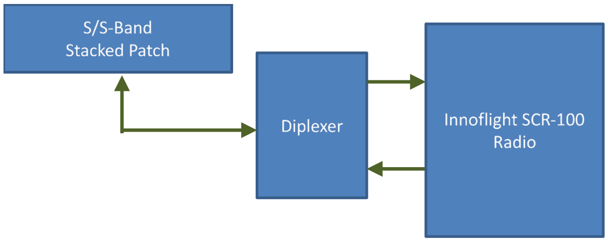

Figure 4: RF Subsystem Block Diagram

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 double the amount of satellite contacts and data thru-put. Therefore, 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.

Figure 6 shows the CAT Augmented End to End Architecture. Additional AWS ground station nodes could be added to keep adding spacecraft contacts. A pricing agreement was worked out with AWS to allow a convenient contact per minute pricing structure.

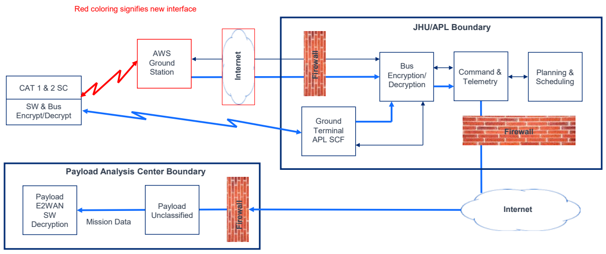

Figure 5: CAT Augmented End to End Architecture

A key objective for the implementation of AWS was to not impact existing systems and integrate without disrupting current mission operations. The use of a digitized IF transport between AWS and the APL SCF was used thus integrating the AWS aperture into the existing signal chain at the SCF. Downlink / Uplink RF communication both utilized an AWS SpectralNet Device to an APL Spectral Net located in SCF. Downstream telemetry paths utilized the existing SCF and CAT MOC interfaces and infrastructure for processing the telemetry data.

Ground Station Control and Status was implanted by having APL Mission Operations Team send commands to control the Cortex ground processor, using the existing remote user connection RUK interface. The MOPs team scheduled both the AWS ground station and the equipment in the SCF (i.e. Cortex, Gatekeeper) for AWS passes

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. The CAT team successfully was able to demonstrate and achieve higher data thru-put from the satellites each day with the combination of the APL 18 meter ground station and the Dublin, Ireland AWS location. 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. The Joint Space Operations Center (JSpOC) officially reported on April 15, 2021 that the two CAT spacecraft de-orbited into the Earth's atmosphere on April 13, 2021.

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. Finally, the AWS ground network was put in place. During this evolution, a secure end to end encrypt/decrypt data flow process was 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. In fact, APL is beginning another mission with Blue Canyon Technologies for three cubesats using our proven mission integration and operations evolution approaches for the Electrojet Zeeman Imaging Explorer (EZIE) Mission.