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Building Satellites in 18 Months:
Lessons Learned from the Rogue Alpha/Beta CubeSats

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ABSTRACT

The Department of the Air Force initiated the Rogue Alpha/Beta Cube Satellite program to challenge The Aerospace Corporation to investigate rapid reconstitution capabilities. The primary objective was to demonstrate swift development of a low cost, small size, weight, and power infrared sensing satellite in Low Earth Orbit via schedule adherence to launch in 18 months. Aerospace achieved this goal by building two identical 3U satellites made with commercial and non-exotic components. The team was dedicated to building, testing, and making sure the spacecraft met all milestones successfully, providing pertinent lessons. First, complications faced during assembly helped lay standards for future use of commercial parts in proliferated networks. Second, the team learned the importance of conducting rigorous inspections to reduce troubleshooting later. Third was the value of developing a commoditized bus to allow for deeper payload focus, especially for satellite constellations. Finally, the team identified the impending need for small, affordable, and swiftly obtainable CNSSP-12 encryption solutions for future Department of Defense missions utilizing small satellites. With the vehicles in space, the team expects to gain valuable information on the infrared sensors used, create a baseline for LEO infrared imaging algorithm development, and evaluate LEO concept of operations for multiple satellites.

INTRODUCTION

In mid-2018, the Department of the Air Force's Space and Missile Systems Center (SMC) began an unprecedented investigation with the help of The Aerospace Corporation (shortly referred to as "Aerospace") to rapidly develop and field a pair of small satellites with low-cost infrared sensors in just 18 months. The goal was to push the limits of SMC's and Aerospace's designing and testing culture for small satellites in order to simulate the ultimate need to replace an inoperable asset, as well as investigate the employment of new and existing techniques needed to meet a compressed development timeline.

To achieve this, Aerospace engineers decided to build off their existing work with Cube Satellites (CubeSats) and concluded that two satellites would be an appropriate measure to demonstrate capability and redundancy. This would not only lend well to a swift manufacturing and assembly schedule, but also provide insight to production needs if the rapid reconstitution concept was applied to a larger constellation of satellites.

The program's narrow schedule also meant that Aerospace would need to construct the majority of these satellites using commercially available and non-exotic components. They utilized a number of rapid prototyping techniques, such as using as many commercial off the shelf (COTS) parts as feasible including a thermo-electrically cooled short-wave infrared (SWIR) sensor.

The team had to rethink its approach to satellite design and risk management; balancing performance with the need to meet the target deadline. Prior to launch, Aerospace completed all environmental testing and system checks; all anomalies were resolved or deemed acceptable with minimal residual risks.

The completed Rogue Alpha/Beta CubeSats consisted of a pair of identical 3U-sized CubeSats, each weighing in under 5 kg. In total, the program was built and launched at a program cost of $4.1 million, including

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labor. The program is still currently active and conducting early on orbit tests.

EARLY MANUFACTUING & TESTING

Parts Selection, Manufacturing, & Assembly

In order to mitigate lead times, The Aerospace Corporation engaged multiple commercial providers to supply the parts needed to begin assembling the Rogue Alpha/Beta CubeSats. This was especially important to the program's commitment to launch an unclassified program in 18 months. Aerospace was able to take advantage of the program's nature and explored the use of many commonly sourced COTS parts. This is a technique used by various universities and smaller government investigations, including some of those done by Aerospace, to keep costs low. However, this carries a certain amount of risk as most commercial parts are not qualified for space, which can cause hardware to degrade fairly rapidly in Low Earth Orbit (LEO). This was one of the first tradeoffs the team made to remain within budget and ensure schedule adherence. Nonetheless, there was little concern about the longevity of the parts given the targeted mission life of one year in orbit.

Despite the CubeSats' short life, all parts were carefully considered, chosen, and sourced. The Rogue Alpha/Beta spacecraft used a plethora of COTS hardware including solar cells, context/visible camera focal plane arrays, reaction motors, batteries, and miscellaneous fasteners to name a few. It is worth noting that while Rogue Alpha and Beta utilized a high percentage of COTS components, few final assemblies of the spacecraft remained untouched or unaltered. For example, the solar cells were sourced from industry, but the panels' printed circuit boards, hinges, and harnesses were custom designed. The same is true for the short-wave infrared sensor that was chosen for both satellites. The payloads required significant effort by Aerospace engineers to adapt the design to provide the desired capability.

The team of engineers initially chose to go with an InGaAs short-wave infrared sensor for a few reasons: relative short lead time and mass availability, sensor balance between size and performance, ability of sensor to operate uncooled, and proven usability of a similar sensor on a previous weather experiments. Similar to the solar panel assembly, the SWIR payload used a COTS camera assembly that was comprised of many custom elements. The lenses, lens housings, baffles, and camera cards were custom designed to make engineering a lens with sufficient optical and thermal properties easier. They these parts were custom, many of them were procured from commercial partners to ensure the components in the payloads could be acquired in large quantities with relatively short lead times at a reasonable cost. At the time and even still, there is not a significant precedence for flying SWIR camera demonstrations on 3U-sized vehicles. One of the first infrared CubeSat missions was performed by The Aerospace Corporation when they flew a similar FLIR Tau SWIR camera and a Tau 640 LWIR micro bolometer on the ISARA/CUMULOS mission. Furthermore, other SWIR sensors at the program's kickoff were only available in small quantities with significant cost and multi-year lead times. The Aerospace team has dedicated vast resources towards developing these types of low cost/size/weight, uncooled, and mass-producible sensors in hopes of making them more readily available for future and larger small satellite programs.

Another measure to keep the satellites as lightweight as possible was not including a propulsion system on the satellites, which is very common for satellites of this size. This also equated to a much simpler system and allowed the team to bypass mandated certifications for handling, testing, shipping, and launching of satellites that do have propulsion systems. No propulsion inherently means that neither of the satellites are capable of altitude adjustments or orbit maintenance, but this was acceptable for the targeted lifetime of the satellites. Despite no propulsion system, the CubeSats are capable of precise pointing via the use of torque rods and reaction wheels.

Each CubeSat weighed in under the threshold target of 5 kg and the final configuration can be seen in figure 1. In total, the design, manufacturing, and assembly process took 14 months. At the end of this process, the team had two identical 3U flight spacecraft that were delivered to the testing team to be subject to various environmental and operational testing.

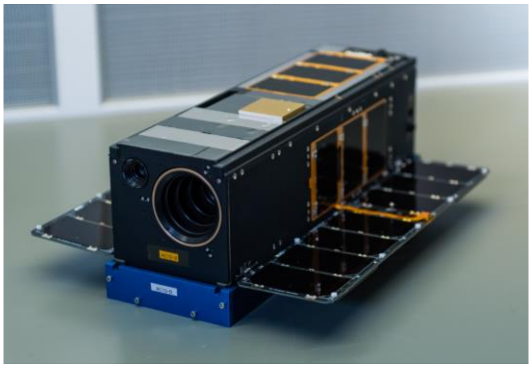

Figure 1: Final Assembly of the Rogue Alpha/Beta CubeSats

Vibration Testing

Both satellites underwent initial random vibration (vibe) tests, conducted using a 2,000 lb.-force shaker. This vibration table was used to perform tests that met National Aeronautics and Space Administration (NASA) General Environmental Verification Standard (GEVS) prototype flight (protoflight) and workmanship levels. All vibe test were performed on each satellite's x, y, and z axes. The testing procedure began with a comprehensive functional performance test (CPT) in order to make sure the satellites' hardware and software were performing as expected before each evaluation. Table 1 shows the specific systems that were tested during the CPT, which was repeated at the end of all vibe tests for comparison.

Table 1: Systems Tested During CPT

Step	System Tested
1	Solar panels produce rated power
2	Batteries charged to expected levels
3	Bus 'safe mode' power at expected level
4	Run day-in-the-life case
5	All bus subsystems operating nominally
6	Payloads respond nominally
7	All mechanisms function properly
8	GPS fixes obtained

The CubeSats were then subjected to different levels and types of vibrations laid out in table 2. First, low level sine sweep tests were done before major testing to create a baseline (via pre-random vibe). This test was performed afterwards to detect any post-test defects.

Dynamic testing consisted of a set of random and sine vibe tests, with inputs of 14.1 Grms per axis and sine burst inputs of 20g at 25 Hz. Vibration level testing at 14.1 Grms was derived from the GEVS requirements for random vibration qualification level testing of flight hardware and components weighing 50 lbs. or less. Meanwhile, the sine burst was developed and is used as a simpler way to perform quasi-static load testing, qualifying the strength of the satellites' structure.

The GEVS random vibration requirements also have a lower level workmanship test of 6.8 Grms. These levels were used in place of protoflight to check the survivability of minor repairs and mitigate harm to other components.

Table 2: Random Vibration Test Protocol

Step	Task
1	Perform Comprehensive functional Performance Test (CPT) before vibe test
2	Secure spacecraft on one of three axes (x, y, or z)
3	Perform sine sweep (pre-random vibe)
4	Perform random vibe (Input: 14.1 Grms, 1 min)
5	Sine burst (Input: 20 g, 25 Hz)
6	Perform Sine sweep (post-random vibe)
7	Repeat steps 2-5 for other axes
8	Perform CPT after vibe test
9	Inspection

Thermal Vacuum Testing

Once both satellites completed and passed all subsequent vibration testing, they moved onto thermal vacuum tests local to The Aerospace Corporation campus in El Segundo, California. The first test performed was to place the CubeSats in a vacuum and test verify that all solar wings released properly in this environment. Thermal vacuum tests then followed, performing both hot and cold operational temperatures (two thermal cycles).

Many operational tests of the hardware and software were also conducted, beginning with running the Attitude Control System (ACS) in hybrid mode, which utilizes the spacecraft star trackers. Additionally, the team tested all payloads (one context, visible light camera and one infrared sensor on each space vehicle) to collect data at frame rates similar to those planned for when in orbit. Command files were successfully uploaded to both satellites while in the chamber. This was done via radio frequency and all commands uploaded were executed on-board successfully. The satellites were also able to share their state of healthy telemetry (including information on voltages, currents, and temperature) that was tracked throughout testing.

ANOMALIES FACED & RESOLUTION

Cracked Solar Cells

After one of the early random vibe tests, significant cracks were discovered on the solar cells of the Alpha space vehicle. While it is common to see minor hairline cracks, these were prominent enough to warrant concern that the cracks could propagate further and stretch across an entire cell (or multiple), creating an

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open loop and rendering the cells useless. The other cells on both spacecraft were inspected, and no major issues were found.

The team deduced that the cracks were most likely created during the soldering process of the solar cells and that vibe tests merely propagated the cracks. In order to reduce this issue in future builds, new soldering fixtures were implemented into the labs to mitigate handling and the amount of stress put onto the solar cells during the soldering process.

While the damage found on the Alpha vehicle's solar cells was not severe, the team ultimately decided to replace the entire wing with a flight-ready spare to give the satellite the best chance at starting its mission with all its anticipated power.

Due to this replacement, the Alpha CubeSat needed to go through another vibe test. This test was performed at workmanship vibe specifications since the team felt that a full protoflight vibe test was not needed for this change, and to reduce the amount of wear on other spacecraft components. Alpha passed this workmanship vibe and inspections revealed that any existing cracks and propagations remained minute.

Solar Power Harness Wear

A separate, full protoflight random vibe test resulted in significant wear on the Alpha CubeSat's solar power wire harness. Both CubeSats have two solar power harness each that transfer the power created by the solar panels to the batteries for recharging. All harnesses were manually routed and secured using Polyimide tape. This is based on previous designs and builds, which have never showed issues. Too much slack in the wire harness had allowed it to shift on top of an adjacent plastic feature during vibe, which eventually led to the observed damage.

The loss of a wire harness would create a significant impact to the power budget as it renders the whole wing useless. The team elected to replace the harness and reroute it with more clearance from any protruding features, using more tape to secure the harness in place. To prevent this occurrence from repeating, all other harnesses were inspected to ensure proper routing clearance and manual installation procedures were updated for future CubeSats. This change alone did not constitute a re-vibe on its own, but it would be tested in subsequent vibe tests later.

Wing Deployment Failure

While the Beta vehicle underwent its initial protoflight level vibe test, it experienced issues properly deploying its solar wings. This was attributed to multiple root causes that became apparent and resolved after various workmanship vibe tests.

The first failure to deploy was traced down to a nut assembly used in a slide release mechanism to deploy the solar wings. The slide release was tested and shown to be operating nominally. After the nut assembly was manipulated manually, the issue was determined to be caused by improper out-of-plane movement and a bias of in-plane movement of the nut assembly.

While designing the release mechanism and nut assembly, the team noticed in past builds that fixing the nut assembly in place led to more issues and far more failures to deploy. Therefore, they designed the nut assembly to allow in-plane side-to-side movement that proved to work successfully on seven other spacecraft. However, it was discovered during inspection that this specific nut assembly had a significant amount of out-of-plane movement. Reinforcement was added to the back of the nut assembly to prevent further out-of-plane movement; however, static testing before a workmanship re-vibe still resulted in inconsistent wing deployment. Further manual manipulation of the nut assembly to either side of its allowed movement showed that there was a bias to one side over the other. Forcing the nut assembly to one bias resulted in four sequential failures, and four deployment tests in the other bias resulted in four successful deployments. Therefore, while the assembly was designed to shift, a shim was installed to force the nut to its favorable bias.

The team performed another vibe at workmanship levels to test the survivability of all fixes. Unfortunately, when testing the wing deployment, the opposite wing (which was not experiencing deployment issues) did not deploy fully. Inspection of the wing found that there was significant resistance due to a protruding screw along the wing hinge (which partially backed itself out during vibe) and was rubbing against the body of the spacecraft. It was eventually concluded that this specific screw was never staked in place with epoxy during assembly.

To limit the chances of any future issues during deployment, all excess epoxy was removed along the wing hinges for both CubeSats, the screw was properly staked down, and all external screws were examined for proper staking. No other screws were found to be without the proper amount of epoxy. The Beta vehicle went through its final workmanship vibe and passed all functional testing.

FROM PRODUCT ASSURANCE TO LAUNCH

ESD, Protection, & Cleanliness

Per standard operating procedure, the completely assembled, tested, and flight-ready satellites were stored in a picosat clean room. When the satellites were not actively being tested, they were stored in a laminar flow bench/hood station. Whenever the CubeSats needed to be handled, all personnel wore electrostatic discharge (ESD) safe coats and gloves. Any and all handling of flight hardware, on or off the satellites, also included a required use of ESD wrist straps.

The Rogue Alpha/Beta CubeSats are equipped with lasers, which are used for communication and data transfer. Whenever personnel supporting any laser tests were in the lab, they were required to have completed the laser safety training and wear protective eyewear at all times. In order to prevent any accidents, there were three redundant hardware protections put in place to prevent any unintended laser activations.

Finally, before the satellites were prepared for delivery, all materials on the satellite were approved for outgassing and all hardware underwent a final clean, inspection, and bake out.

Transportation and Delivery

After a Pre-ship Review was completed, the team worked to wrap up the transportation process to prepare the CubeSats' journey from El Segundo, California to delivery to NanoRacks in Houston, Texas. The first step was to protect the context and SWIR cameras by installing temporary plastic covers, shown in figure 2. Then the spacecraft were individually wrapped in anti-static bags and packed into a hard case lined with foam and suited with shock sensors.

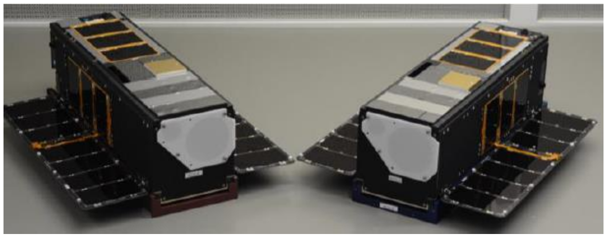

Figure 2: Rogue Alpha/Beta CubeSats Preparing for Transport

The team then transported the CubeSats to a NanoRacks facility, where they were transferred to a 10k clean room for incorporation into the NanoRacks deployment pods. Aerospace personnel aided NanoRacks in unpacking the space vehicles, performing final functional tests, and integration. All personnel were required to follow all previously established ESD procedures as well and wear lint free gloves to limit contamination, see figure 3. After the CubeSats were placed in their launch pods, they would remain there until their deployment.

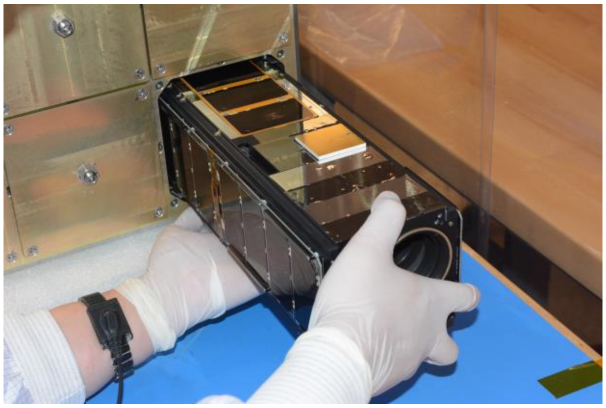

Figure 3: CubeSat being Integrated into NanoRacks Deployment Pods

NanoRacks then delivered the deploy complement to NASA's Wallops Flight Facility for integration into the Northrop Grumman Cygnus capsule. Throughout this time, the vehicles were constantly kept in a secure and clean environment.

Launch & Deployment

On November 2, 2019, the Space and Missile Systems Center, The Aerospace Corporation, NASA, Northrop Grumman, and others celebrated a successful launch out of the Mid-Atlantic Regional Spaceport's Pad-0A at NASA's Wallops Flight Facility in Virginia.

The Rogue Alpha/Beta CubeSat program launched aboard a Northrop Grumman Antares 230+ configuration launch vehicle. The 230+ configuration allows the Northrop Grumman Cygnus capsule to deliver up to 1,760 lb. (800 kg), which carried the Rogue Alpha and Beta, among other cargo, to the International Space Station (ISS). This launch signified the conclusion of all ground efforts and the start of Alpha and Beta's voyage in orbit, as well as the success of the 12th commercial resupply mission awarded by NASA. The Cygnus NG-12 capsule quickly made its way and docked to the ISS.

While the Rogue Alpha/Beta CubeSats successfully made it to space on November 2, they remained stored on the ISS until the capsule's release on January 31, 2020, shown in figure 4. The team received confirmation of the successful deployment of Alpha at 1:00 pm PT and Beta at 4:10 pm PT. Though released at a considerable time apart from each other, their scheduled releases allowed the CubeSats to orbit a few hundred kilometers apart. From there, the team waited for the first opportunity to make contact with both vehicles. Once initial contact was made, the operations team immediately began a state of health check. Both assets confirmed nominal battery health and their telemetry data provided more accurate information about their orbits. The team used this to update a locally sourced orbit-tracking tool to help get a better understanding on the CubeSats' locations.

Figure 4: Cygnus NG-12 being Released to Deploy both CubeSats before Reentry

LESSONS LEARNED

Raising COTS Standards

During the manufacturing, assembly, and early testing of the Rogue Alpha/Beta CubeSats' parts, the crew faced two major non-conformances related to the commercial off the self parts being used. Aerospace engineers worked extensively to determine the root causes, fix the anomalies, and do other safety checks on similar components. Collectively, these efforts cost the group nine weeks in delays, but with no overall delay on delivery to the launch provider.

1. Focal Plane Array Connectors: The first issue was observed in the form of elevated data values when testing the payload. The cause of the issue was eventually traced to the focal plane array (FPA) connectors. Upon inspection, there was a notable fracture in one of the solder joints at the interface between the FPA pins and the electronics board. The team concluded this was caused by poor solder wetting on the gold-plated pins. This ultimately led to a break between the pins and solder when manually mating and disconnecting the connectors. To save the work done to the payload and to mitigate further delays, Aerospace disassembled the COTS FPA connectors and reflowed solder on the connections.

   In order to mitigate potential reoccurrences, this same inspection and repair was done to the other payload and to a flight ready spare. (Other boards ordered in this lot were also inspected, but no issues were found.) In addition, the team executed extensive post repair testing prior to environmental tests.

   Overall, the team spent six weeks and many hours to find the root cause and resolve this issue. Aerospace also notified the vendor to prevent future issues with new parts.

2. Camera Board Communication Failure: Another issue identified early on was a failure to transfer data from the camera on the Alpha vehicle. This issue was eventually traced to cracks in the 39-pin harness of the camera board. The team has confidence that this was caused by a defect related specifically to the gold plating used on the copper connectors which cracked when handled. At this point, the use of these 39-pin harnesses was known to create issues due to their delicate nature. The space vehicles' design was based on a heritage system which has suffered from similar issues. In an attempt to fix this issue, the harnesses were replaced on the Alpha spacecraft with ones that were in acceptable condition. After looking at the hardware that had been replaced, numerous hairline cracks were discovered that had not yet led to failures.

   The Beta vehicle continued to suffer from this issue despite since it was unable to receive a component in better condition due to the poor shape of the other components and replacements. During thermal vacuum tests, the context camera failed to transfer data to the board. Aerospace engineers affixed a shim to resolve the connection cracks, which proved to maintain integrity throughout ground testing. There is still a possibility that the fix may fail during launch or its operational life, however, this has not proved to be an issue so far.

   In total, it cost 3 weeks of schedule to determine the cause and perform repairs on these harnesses. As a result, the Aerospace team has more awareness on the flaws of using such a delicate component and have worked to create a new baseline design that phases out the use of these harnesses.

Note that these issues are not to the fault of the vendors, but rather inherent risks of using COTS parts. It is a byproduct of buying mass produced, readily available, and affordable parts. These commercial parts do not typically need to be held to the high standards of assembling a satellite. As a result, the Rogue Alpha/Beta CubeSat team recommends that programs implement a higher level of screening and acceptance at the vendor or local level. One such way could be through an inspection by the vendor or the customer, and/or by having the vendor provide workmanship certification for each part or the entire lot of parts. The team recognizes that this may increase the cost of the parts, but it may be worthwhile compared to the labor-hours and schedule costs that may come later.

Commoditized Bus

It was also recognized that even in this small project of two CubeSats, to produce a constellation of satellites quickly and affordably, it benefits to invest in commoditizing or acquiring a reproducible bus.

For smaller projects such as the Rogue Alpha/Beta CubeSat program, having identical satellites proved to be extremely useful. Many of the parts were interchangeable meaning that spares purchased were readily available for both. This also means less overall program costs as the sharing of parts means less spares are ordered. Another benefit of having a reproducible bus is that subsequent builds get done faster and make lessons more relevant compared to ones learned from one-off designs. Specifically, the team was frequently able to use lessons learned from prior generations to anticipate what to expect on these CubeSats. For larger satellites, the improvement period is spread further apart and may reach a point where it loses value or never gets used. Additionally, having a standard bus allows for more attention to be lent to payload development and refinement.

The benefits of using a commoditized bus carries many benefits. It is expected that eventually more industry leaders will become interested in making mass produced satellite buses, instead of one-off designs, to meet needs.

Utilizing Rigorous Inspections & Prototypes

No matter if commercial parts or a replicated design are used, the CubeSat assembly team for this program identified the value of employing the use of multi-stage inspections and prototype research.

In regard to this program, an issue was faced by way of a screw not being staked down with epoxy, leading to a significant issue resulting in improper solar wing deployment. If a more rigorous inspection process was exercised, it may have been able to catch this problem sooner. A possible fix could be implementing a two-person inspections process to have a redundancy plan.

Even so, it helps tremendously when knowing what to look for. The failure in the camera board pin harness and cracks in the solar cells were easily resolved because of insight from previous iterations. However, there are instances when the issue may not be apparent until it is noticed in performance testing where it may be too late. This is what makes prototypes so invaluable. They act as a means of risk reduction by flushing out early, unforeseen issues and optimizing procedures for future or larger programs.

If a proliferated system is to be designed, the CubeSat team recommends employing both of these measures as a means of reducing the amount of issues faced long term. This can also lead to more time and effort to be dedicated to the development of the payload.

Swift & Affordable Encryption Solutions

The Rogue Alpha/Beta CubeSat program is not a National Security Space mission and therefore did not require National Security Agency (NSA) approved encryption. As a result, the team decided to use an in-house encryption solution proven on other unclassified CubeSat programs. However, the program looked into encryption options as part of the trade space. A crucial take away is the identified need for lightweight, small, speedy, and economic NSA compliant encryption solutions.

At the time Rogue Alpha/Beta were designed, there was only one compliant encryption solution available that was a potential fit, however, the lead time to acquire it would have pushed the schedule much longer than allowed. There are often lengthy year-plus lead times before an encryption solution is approved or acquired. Additionally, the cost to integrate that solution would have exceeded the entire budget of the program. The spacecraft design team eventually decided that the best option for this unclassified, one-year research investigation would be an in-house encryption solution. Previous Aerospace CubeSat programs served as precedence for proving this solution’s effectiveness, which was able to suit this program better than the alternative.

Currently, the list of NSA compliant encryption options has improved with more compact solutions available in shorter lead times. This could not come at a more pertinent time as the Department of Defense seeks to expand its partnerships with more commercial and university partners. In order to help these programs remain successful, the Department of Defense must continue to investigate even more ways to offer encryption solutions that can be obtained in short timelines and under small budgets, all while maintaining an attractive form factor for small and medium-sized satellites.

LOOKING FORWARD

At this time, the Rogue Alpha/Beta CubeSats have been operating in space for a few months. The main goals are to gain valuable information on the infrared sensors used, create a baseline for LEO infrared imaging algorithm development, and evaluate LEO concept of operations (CONOPS) for multiple satellites. The infrared sensors will fly dominantly in a horizon-pointed configuration to collect frame stacks that can be used for testing cloud scene processing algorithms and clutter models. The team will command both satellites simultaneously in forward, aft, and cross-track pointing configurations, collecting scenes in benign, intermediate, and stressing solar conditions. At present, the program has focused on calibrating the CubeSats' sensors and observation tasking has been minimal. Since the Rogue Alpha/Beta CubeSats have achieved on-orbit operation prior to other upcoming LEO concepts, the anticipated information gathered on cloud backgrounds, multi-frame processing, and LEO CONOPS will prove to be especially useful.

The program is approximately halfway through, yet there have been substantial improvements that can be shared with the intent of helping further CubeSat technology at large. The Rogue Alpha/Beta team hopes that these lessons can serve some relevance to programs big and small as there have been multiple instances in this project alone where time and effort have been saved because of the insight provided by others.

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