A Sat-to-Sat Inspection Demonstration with the AeroCube-10 1.5U CubeSats

Joseph W. Gangestad, Catherine C. Venturini, David A. Hinkley, and Garrett Kinum
The Aerospace Corporation
2310 E El Segundo Blvd, El Segundo, CA, 90245; (310) 227-6783
joseph.gangestad@aero.org

ABSTRACT

In the summer of 2020, the pair of AeroCube-10 1.5U CubeSats completed a series of mutual proximity operations as close as 22 meters separation and captured several sets of satellite-to-satellite resolved imagery, inspecting all faces of a vehicle in each pass with a resolution less than 8 mm. AeroCube-10 was designed and built by The Aerospace Corporation with the primary missions of atmospheric science and the maturation of nanosatellite technologies, including a new star tracker design, warm-gas propulsion system, GPS receiver, and a low-noise focal plane. Investigating the possibility of using CubeSats for satellite inspection missions, the AeroCube-10 team designed an experiment using these technologies in ensemble to bring the vehicles close together and demonstrate the feasibility of inspection missions in a package as small as 1.5U. Starting from a separation of more than one thousand kilometers, over the course of several weeks maneuvers executed with the AeroCube-10 propulsion unit brought the vehicles closer together, using proven formationkeeping techniques to ensure safety of flight as the range dropped below 100 meters. The first imagery while in a natural-motion circumnavigation (NMC) was performed at a range of 64 meters. Gaining confidence in AeroCube-10's capabilities, the operations team decreased the size of the NMC several times, obtaining imagery at 30 meters and then 22 meters. AeroCube-10 completed roughly one fourth of an NMC during each imaging run, and the observing satellite collected images of all faces of the target as it orbited around. At such close range, the inspection images clearly show individual solar cells, patch antennas, the exposed atmospheric probe magazine payload, the satellite's miniature radiation dosimeter, and other features. AeroCube-10's activities have demonstrated for the first time the feasibility of prolonged inspection activities in a very small form factor and, by closing from great distance and then entering NMC, proved that the nanosatellite platform has the potential for multiple-target inspection, as may be necessary for space-debris removal or constellation-inspection missions.

INTRODUCTION

AeroCube-10 is a pair of 1.5U CubeSats that were designed and built by The Aerospace Corporation to support internal technology maturation efforts and an atmospheric science experiment. The two vehicles, AeroCube-10A (catalog object 44485) and AeroCube-10B (object 44484), launched on 17 April 2019 as secondary payloads on a Cygnus resupply capsule to the International Space Station. After a subsequent undocking and orbit raising, the Cygnus capsule released AeroCube-10 into a 470 x 485 km altitude orbit at 51.6 deg inclination on 7 August 2019.
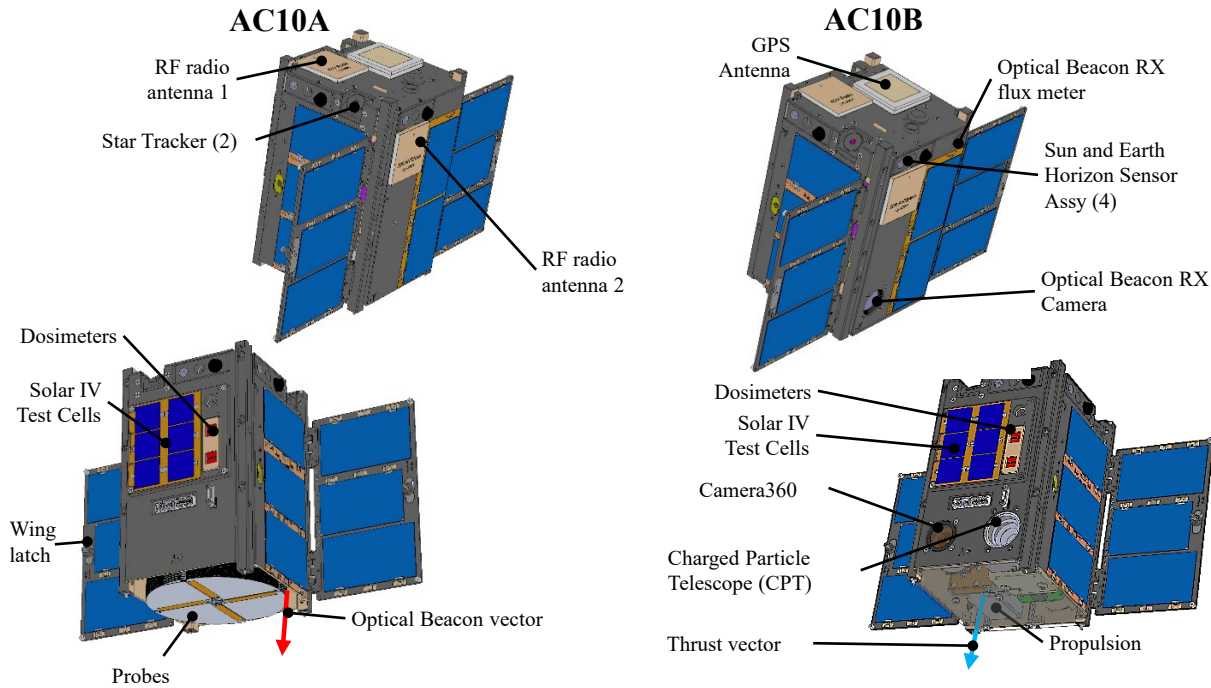
Figure 1 shows the physical design and layout of both AeroCube-10 vehicles. Each 1.5U CubeSat consists of a 10 x 10 x 15 cm bus and two 9 x 13 cm solar panel wings.

The primary payload on AeroCube-10A (AC10A) is an atmospheric probe magazine, which releases small aluminum deployables with a high area-to-mass ratio that decay quickly due to atmospheric drag. The decay behavior of the probes provides the experiment leads with insights into atmospheric density and paths to improved density modeling. AC10A also carries an optical beacon that provides a visual reference for testing the efficacy of new control algorithms in support of Aerospace's long-running efforts in nanosatellite laser communications.[6]

AeroCube-10B's (AC10B) primary payload is a propulsion system, described in greater detail below, that provides a modest amount of thrust and ΔV and was included in the design to enable simple formation control, such as of in-track range, which supports space-to-space experiments with the optical beacon on AC10A and probing spatial variation of radiation between the vehicles. AC10B also carries secondary payloads supporting radiation dosimetry experiments, including a charged particle telescope.

The major subsystems and payloads relevant to this paper are described in greater detail below.

AC10A

RF radio antenna 1

Star Tracker (2)

RF radio antenna 2

Dosimeters

Solar IV Test Cells

Wing latch

Optical Beacon vector

Probes

AC10B

GPS Antenna

Optical Beacon RX flux meter

Sun and Earth Horizon Sensor Assy (4)

Optical Beacon RX Camera

Dosimeters

Solar IV Test Cells

Camera360

Charged Particle Telescope (CPT)

Thrust vector

Propulsion

Figure 1. Physical design and layout of AeroCube-10.

Attitude Control

The AeroCube-10 vehicles are 3-axis stabilized, using Aerospace's suite of heritage attitude-determination sensors and attitude-control mechanisms.[7] Gross pointing knowledge and control is provided by Sun and Earth-horizon sensors and magnetic torque rods, and precise knowledge and control from star trackers and reaction wheels, all of which were developed in house. AeroCube-10's star trackers are a new design, leveraging advances in black silicon technology to yield a unit with ultra-low size, weight, and power.[9] With this system, AeroCube-10's attitude control system (ACS) can achieve roughly 0.01 deg of pointing knowledge and 0.1 deg of pointing control.

Navigation

Both AeroCube-10 vehicles carry an in-house developed GPS receiver (GPSR) that has flown on more than two dozen of Aerospace's CubeSats since 2011.[4] The GPSR collects fixes based on a pre-set schedule—typically at regular intervals over one or two orbits once a day—and downlinks the fixes for processing. Operators process the GPS fixes with precision orbit-determination (OD) software on the ground to generate ephemerides for each vehicle and propagate forward in time as necessary. The GPSR uses only the L1 GPS signal for solutions, and each individual fix has an error of 5- 10 meters (1σ), which is an improvement over the historical performance in

[4] thanks to progressive upgrades, and the precision OD solution using the fixes in ensemble has an error on the order of single-digit meters. AeroCube-10's GPSR was modified also to collect the L2 GPS signal to support the mission's atmospheric science experiments, but the L2 signal is not used in the navigation solutions.

Propulsion

AC10B's propulsion system is the second generation of a design that flew twice on the AeroCube-7 series of spacecraft.[8] The propulsion unit uses steam as the primary source of thrust by heating a small tank of water in advance of desired maneuvers and releasing the resulting steam to effect a change in velocity. The total thrust produced is approximately 4 mN, and the 30 g tank can yield at most a total ΔV of 6 m/s at an Isp of ~70 s. The largest single practical maneuver, limited by the attitude control system's ability to compensate for induced torques, is approximately 10 cm/s, but most maneuvers have been limited to between 1 mm/s and 3 cm/s. The propulsion system's performance is focused on formationkeeping and proximity operations and is not suitable for creating substantial orbit changes or for disposal.

Imaging

AC10B carries a single camera with a 16 mm aperture and 29.5 deg field of view (FOV). The camera uses a monochrome SiOnyx XQE-0920 focal plane, which is the same used for the star trackers. The imager's 1280 x
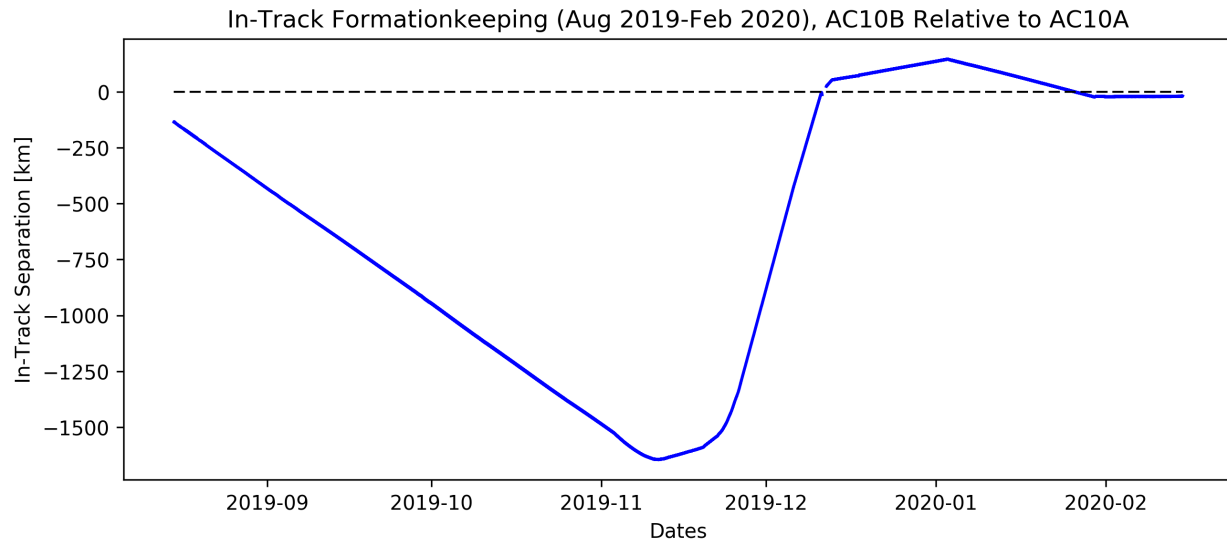
Figure 2. In-track formationkeeping of AeroCube-10 during the first six months of the mission, showing the first maneuvers in November 2019 that arrest the vehicles' separation and brought them back together by early December. Throughout February, the satellites maintained an in-track separation of 20-22 km.

720 pixels provided an instantaneous FOV (IFOV) of 0.02 deg.

CHECKOUT AND FORMATIONKEEPING

AeroCube-10 was deployed on orbit on 7 August 2019, and checkout began immediately thereafter. Over the course of several weeks, the attitude control system was calibrated and initialized, and checkout of the propulsion system on AC10B began later in November 2019 due to prioritization of other mission demonstrations.

Figure 2 shows a plot of in-track separation (AC10B relative to AC10A) for the first six months of the mission. After deployment, the two vehicles were separating at a rate of ~25 km/day due to initial deployment transients. By November, the vehicles had drifted ~1,600 km apart, and the first priority was to arrest the separation and bring them back together. A series of small maneuvers (ΔV = 1.5 cm/s) in November slowed and then reversed the relative drift rate, and by early December, the two satellites were together again, coming as close as 2 km. Throughout January, more maneuvers were performed to calibrate the propulsion system's performance and to realign the relative orbit. In February, the satellites maintained an in-track separation of 20-22 km.

While in close proximity, ensuring safety of flight is of paramount importance. To avoid the possibility of collision between the two AC10 vehicles and to design subsequent close approach activities, operators used the methodology described in D'Amico and Montenbruck[2] to maintain a passively safe formation. Maneuvers

performed early in 2020 not only maintained the in-track formation of the satellites but also re-oriented their relative eccentricity and inclination vectors so that AC10B followed a spiral motion around AC10A's orbit. In such an orientation, in-track position uncertainty (which dominates the ephemeris uncertainty) creates no risk of conjunction because the two satellites' orbits never intersect anywhere. As long as the size of the spiral is larger than the cross-track and radial uncertainty (typically 1-3 meters with AC10's GPSR), operators can proceed with confidence that the vehicles are not at risk of collision.

Through the first six months of operations, successful demonstrations of the new star trackers and upgraded ACS, the propulsion system's ability to deliver very small maneuvers (on the order of mm/s) reliably, navigation-data processing, and the camera's sensitivity increased the operators' confidence in performing more stressing activities.

Active debris removal[3] and satellite-to-satellite inspection[1,5], have become increasingly relevant missions for the space community, and following the successful completion of some of AeroCube-10's primary mission, the team considered the possibility of using these 1.5U vehicles to demonstrate the prerequisite proximity operations and resolved imagery for future dedicated inspection missions.

Operational Constraints

AeroCube-10 was not envisioned during the design phase to perform close proximity operations or satellite-to-satellite inspection, and consequent operational

constraints with the vehicles' subsystems and payloads limited the number and frequency of opportunities to demonstrate inspection activities. Some of the constraints that operators had to overcome included:

Attitude control. Stray light contamination in the star trackers required all ACS initializations to occur during or shortly before or after eclipse. Through much of the daylit portion of the orbit the satellite must ride the gyros, which could yield several degrees of pointing error after 20-30 minutes of flight on the daylit side.

Navigation. The GPS receiver uses the L1 signal only for navigation solutions, yielding fixes accurate to 5-10 meters and a processed ephemeris accuracy slightly better. The OD process is performed ground-in-the-loop, and pointing plans for proximity operations and inspections must be uploaded several hours in advance depending on access to Aerospace's ground network. The multi-hour propagation could add tens of meters of error to the relative ephemeris between the vehicles.

Imaging. AC10B's camera has a large FOV that requires very close proximity (<100 m) to resolve a 1.5U target as an extended object. Also, the minimum exposure time is 20 μs, which is long enough to overexpose and saturate the focal plane if a cloudy Earth is in the frame.

Propulsion. The warm-gas unit must warm up the water propellant >20 min advance of a burn, which consumes substantial power and prevents leaving the unit on indefinitely. There is also an uncertainty of ~2 deg between the thrust vector and the body frame of the AC10B vehicle for any given maneuver, which for cross-track or radial burns can introduce a roughly 4% component of the burn's ΔV in the in-track direction.

Mass Properties. The release of atmospheric probes from AC10A during its science mission introduces a mass differential between the vehicles. The release of each probe increases the mass differential by ~1 percentage point, triggering differential drag that can deteriorate the necessary alignment for natural motion circumnavigation in less than a day. (The release of water from AC10B's propulsion unit has a negligible effect on the mass properties. The mass of all the water propellant stored on AC10B is equivalent to one probe.)

Notwithstanding these constraints, the team elected to proceed with a series of attempts to enter close-range proximity operations and collect resolved imagery between the AeroCube-10 satellites.

OPERATIONS PLANNING

Each AeroCube-10 vehicle uses a pair of 915 MHz patch antennas and an in-house-developed radio to communicate with Aerospace's network of ground stations located across the continental United States and Hawaii. Communication with the satellites is only possible through the ground network, and although the longitudinal dispersion of sites provides frequent high-elevation contacts (typically 6-8 per day), access gaps of up to 8 hours occur roughly each day.

All operations planning occurs ground in the loop. The satellites do not have on-board navigation (i.e., they can neither process GPS data into an ephemeris on board nor use GPS data for operations in real time), and they have no crosslinks to share data.

To execute an activity as challenging as proximity operations and inspection, the planning cycle proceeded in four steps:

1. **Pre-event orbit tuning.** In advance of performing inspection runs, the operations team decides how close they would like to attempt the activity and over what timeframe. These choices lead to the planning and execution of maneuvers in the week or two leading up to the events. The maneuvers shape the relative orbit of AC10B with respect to AC10A to create the desired conditions (e.g., setting the size of the cross-track and radial spiral motion, which impacts the range at closest approach).

2. **Navigation data collection.** In advance of an opportunity, both AeroCube-10 vehicles collect GPS data. The GPSR collects fixes every 10 minutes for one or more orbits, as prescribed by operators, over 1-3 days. Multiple days of fixes are valuable to capture sufficient signal of the drag forces acting on the satellites.

3. **Operations planning.** The GPS data are downlinked and processed using in-house high precision OD software. The best opportunities for an inspection run are identified based on range, lighting conditions, and the locations on the orbit that are suitable for precision attitude control. When the opportunity has been selected, the operators prepare a plan for the ACS and imaging payloads and uplink the plan at the earliest possible opportunity. Ideally, the time from downlink of GPS data to plan preparation to opportunity epoch is no more than 12 hours, and preferably less than 6

hours. The shorter the time, the lower the risk of failure due the staleness of ephemerides that were used to prepare the pointing plans.

4. **On-orbit execution and evaluation**. The satellites carry out the proximity operations and inspection plan open loop. Imagery from the event is downlinked over several passes and evaluated for success or failure.

Although the AeroCube-10 satellites do not have an on-board capability to exploit navigation data or imagery in real time, the operations team considered the possibility of using AC10B's camera to perform supplemental angles-only navigation with respect to AC10A. In addition to the resolved imagery that appears below from inspection activities, AC10B was tasked on several occasions to collect images of AC10A while at distances >1 km and when lighting conditions were favorable to capture the satellite as a point source.

An experimental navigation frame taken by AC10B appears in Figure 3, where the monochrome color scale has been inverted to highlight relevant features and artifacts. At the time of the image capture, AC10A was 1.8 km away and appears in the center of the frame. AC10A has an apparent visual magnitude of approximately –3.3 and with the 10 ms exposure time appears as a saturated point source. A small number of stars are visually discernible in the field as well.
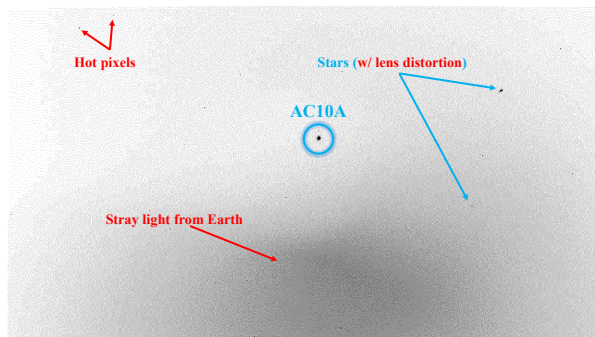
Exposure Time: 10 ms
Range: 1.8 km

Figure 3. An experimental angles-only navigation frame taken by AC10B, in inverted greyscale. AC10A is in the center of the frame, and assorted undesirable artifacts are highlighted, including hot pixels, lens distortion, and stray light.

In addition to hot pixels and lens distortion, which can be compensated for, stray light contaminates much of the frame. The tangent to the line of sight from AC10B to AC10A is close to the horizon, and light from the sunlit Earth fills the bottom third of the FOV. Longer exposure times would wash out most of the FOV with stray light.

The usefulness of the frame in Figure 3 for navigation is minimal, and the operations team determined that most candidate mitigations were unlikely to increase the images' utility. Increasing the exposure time would bring more stars above the detection threshold for navigation, but AC10A itself would saturate and bleed even more severely, inhibiting an accurate determination of its relative position with respect to the reference stars, and the stray light would wash out most of the FOV. With a lower exposure time, stray light and AC10's saturation are mitigated at the expense of detectable stars, which would ruin the image's usefulness for navigation. Frame stacking with very short exposure times may overcome some of these effects, but the time-varying and non-uniform stray light would continue to compound as images are added and cannot be easily mitigated.

Overall, this experience with AeroCube-10 demonstrated that angles-only navigation in LEO would require a substantially more sophisticated suite of sensor hardware. A viable solution would have to balance stray light rejection, FOV size, minimum detectable magnitude, and saturation limits, most likely with a combination of hardware (e.g., baffles, low read noise), software (e.g., compensation for characterizable artifacts like lens distortion), and collection cadence (e.g., frame stacking), not to mention opportunities afforded by other wavelength bands (e.g., infrared).

CLOSE APPROACH #1: 4 APRIL 2020

The first step in achieving satellite inspection was to reduce the overall size of the satellites' relative motion. Following deployment and orbit cleanup with the propulsion system, AC10B's passively safe spiral around AC10A's orbit had a radius of ~175 meters, too
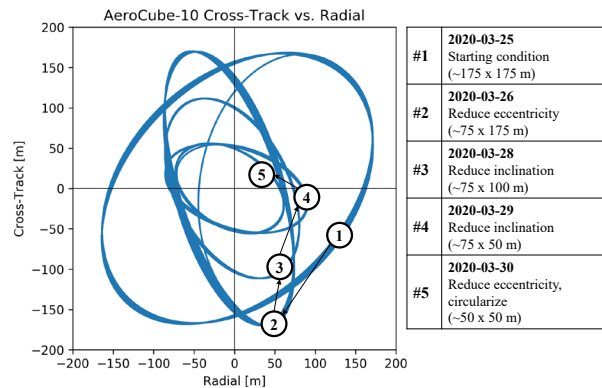

Figure 4. Cross-track and radial size reduction of AC10B's orbit relative to AC10A in advance of close approach #1.
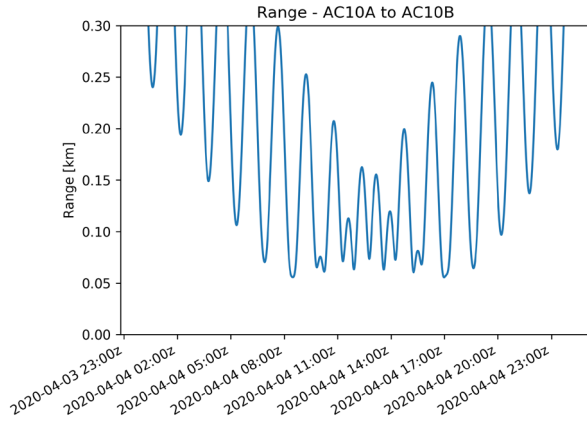
Figure 5. Range between AC10A and AC10B on 4 April 2020, with closest approaches of ~50 m.

distant to hope for a resolved image of AC10A. Figure 4 shows the reduction in size of the cross-track and radial spiral to ~50 meters radius over five days in March 2020, when AC10B performed five maneuvers to change eccentricity and inclination according to the scheme of D'Amico and Montenbruck.[2] The cross-track and radial motion in the plot in Figure 4 never intersects the origin, ensuring that there is no chance of contact between AC10A and AC10B, and the operators can be assured that the relative motion is passively safe. At the same time, in-track components of the maneuvers brought the satellites closer together in range, starting from >3 km to closest approaches of ~50 m, as shown in Figure 5.

As the satellites passed each other, AC10B succeeded in collecting three frames that included AC10A from a range of 64 m. Figure 6 shows one of these frames, where one face of AC10A and its solar panel wings are
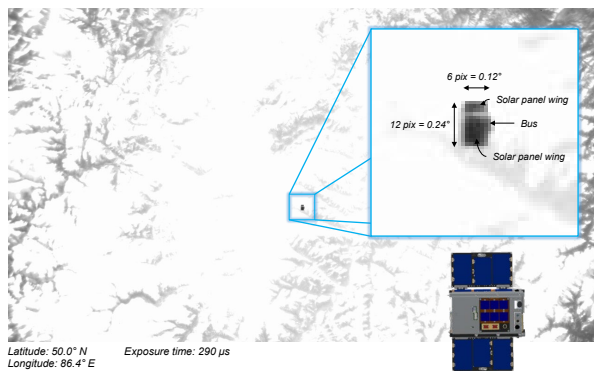
Figure 6. One frame collected by AC10B on 4 April 2020 at 11:56:29.13z at a range of 64 m, showing one face of AC10A and its solar panel wings. The superimposed CAD model represents the approximate orientation of AC10A in the scene.

discernible, extending roughly 6 x 12 pixels in the scene. The lighting conditions were not ideal during this close approach, and the snowcapped mountains of central Asia in the background overexposed much the image while the satellite was partially illuminated from the side.

The success of this close approach imagery, and the associated processes on the ground developed to enable it, encouraged the operations team to attempt the activity again. This first close approach did not involve an outright inspection, as only three frames of one face of AC10A were captured, but an assortment of unknowns related to such an operation—such as appropriate image exposure time, GPS collection cadence, and ACS pointing strategy—had been settled.

CLOSE APPROACH #2: 17 JUNE 2020

Further attempts at proximity operations were delayed until June 2020 due to prioritization of the AeroCube-10 primary missions. When the satellites were free, the operations team began reestablishing the orbital conditions for a close approach, including a further reduction in the size of the cross-track and radial spiral to 30 x 60 m. Starting on 12 June, a series of maneuvers were executed to bring the satellites together again, starting from a range of ~250 m. Figure 7 shows the in-track distance between AC10A and AC10B over six days, including four maneuvers.

By June 2020, AC10A had released three atmospheric probes, creating a 3% mass differential between the vehicles. Differential drag consequently manifested itself in a matter of hours, making a truly stationary NMC impractical to maintain. The operations team sought to create a scenario where AC10B would begin slightly *ahead* of AC10A and let differential drag pull
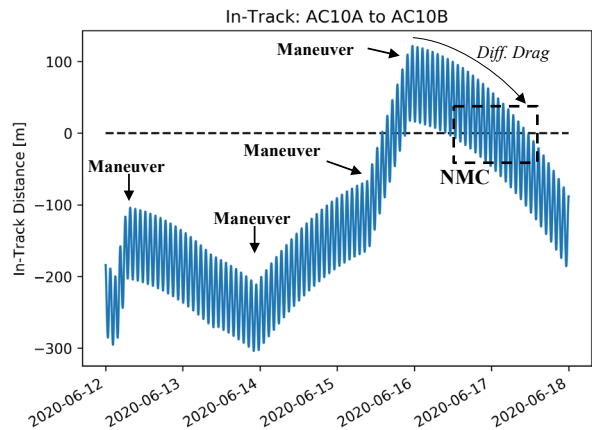
Figure 7. In-track motion leveraging maneuvers and differential drag to yield a ~24-hr period of drifting NMCs for AeroCube-10 in June 2020.

the vehicles together slowly together into a series of drifting NMCs. In Figure 8, the penultimate AC10B maneuver was planned to overshoot AC10A (at zero in the plot) and the last maneuver to match orbits and halt all in-track drift. At that point, differential drag became the dominant relative force, and AC10B began to drift back towards AC10A. On 16 and 17 June 2020, the two

Latitude = 34.2 N, Longitude = 30.4 E
Range = 44 meters
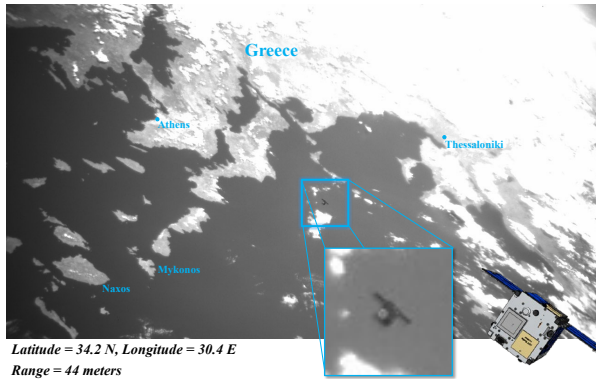
Figure 9. Frame collected by AC10B on 17 June 2020 at 08:40:05.12z at a range of 44 m. AC10A's bus, wings, and some surface features (e.g., square GPS patch antenna) are distinguishable.

vehicles passed each other over a period of ~24 hours.

The ideal NMC behavior occurred on 16 June at 2200z to 17 June 0800z, which also coincided with ideal lighting conditions, with the sun at AC10B's back fully illuminating AC10A. Following a successful attempt to collect a small number of frames around 0232z in the same manner as the close approach in April, the team planned a series of collects over 22 minutes, starting at 0825z and covering about one fourth of an NMC, from furthest separation and passing through a closest approach. This NMC run collected 12 frames, one of
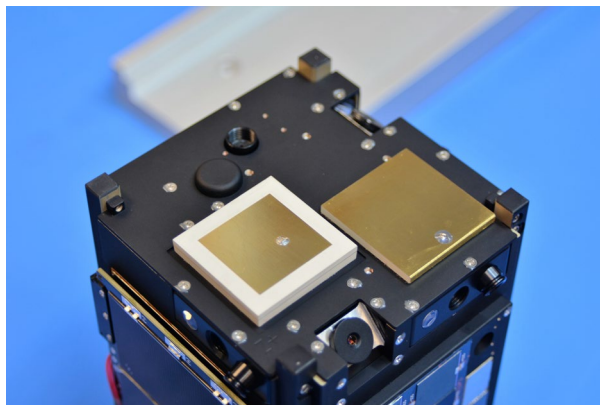
Figure 8. The +Z face of AC10A, which includes the white-bordered GPS patch antenna that appears prominently in inspection images.

which appears in Figure 8 when the satellites were 44 m apart.

At a range of 44 m, the frame in Figure 8 offers a resolution of ~1.5 cm, which is sufficient to distinguish some surface features. AC10A's square GPS patch antenna stands out as particularly bright against the black anodized aluminum bus and wings. This antenna appears prominently in all the inspection images due to its matte white outline. Figure 9 includes a picture of the as-built AC10A and its +Z face, which includes the GPS patch antenna.

A composite of all 12 inspection images of AC10A appears in Figure 10. The combined in-plane and out-of-plane motion during the NMC provided AC10B with a view of four (of six) faces of AC10A during the collection period. The collections began with the image in the upper left of Figure 10, at a range of 56 m, and concluded with that in the lower right at 35 m. AC10A was not subject to attitude control at the time of the event and was tumbling.

This series of images demonstrates the myriad challenges of planning an effective satellite inspection. If the target is uncooperative (or, similarly, tumbling), there is no way to guarantee full coverage across all faces. Indeed, the most noteworthy payload on AC10A is its atmospheric probe magazine, which is exposed to space, but the face containing the magazine was one of the two faces not imaged during this inspection.

The inspection images also suffer from a wide range of background brightness. The earliest images from the collection, which were omitted from Figure 10, had a background of black space, and the Figure 10 images vary between bright and overexposed clouds, middling-bright landmass, and comparatively dark sea. Planning the exposure times ahead of such an inspection run is challenging, because the correct exposures depend as much on knowledge of the weather (e.g., clouds) as on whether just the Earth or space will be in the background.

A more sophisticated auto-exposure system is no guarantee of success. Because the images are dominated by the background, automatic compensation without knowledge of the target's appearance or response runs the risk of losing the target's signal while optimizing for the background. In Figure 6, AC10A occupies only 0.008% of the pixels in the image, and the primary reason the satellite and its gross features are visible at all is because of the (inadvertent) overexposure of the background. If the exposure time were shorter and the snow-capped mountains properly exposed, there is a high probability that the sub-
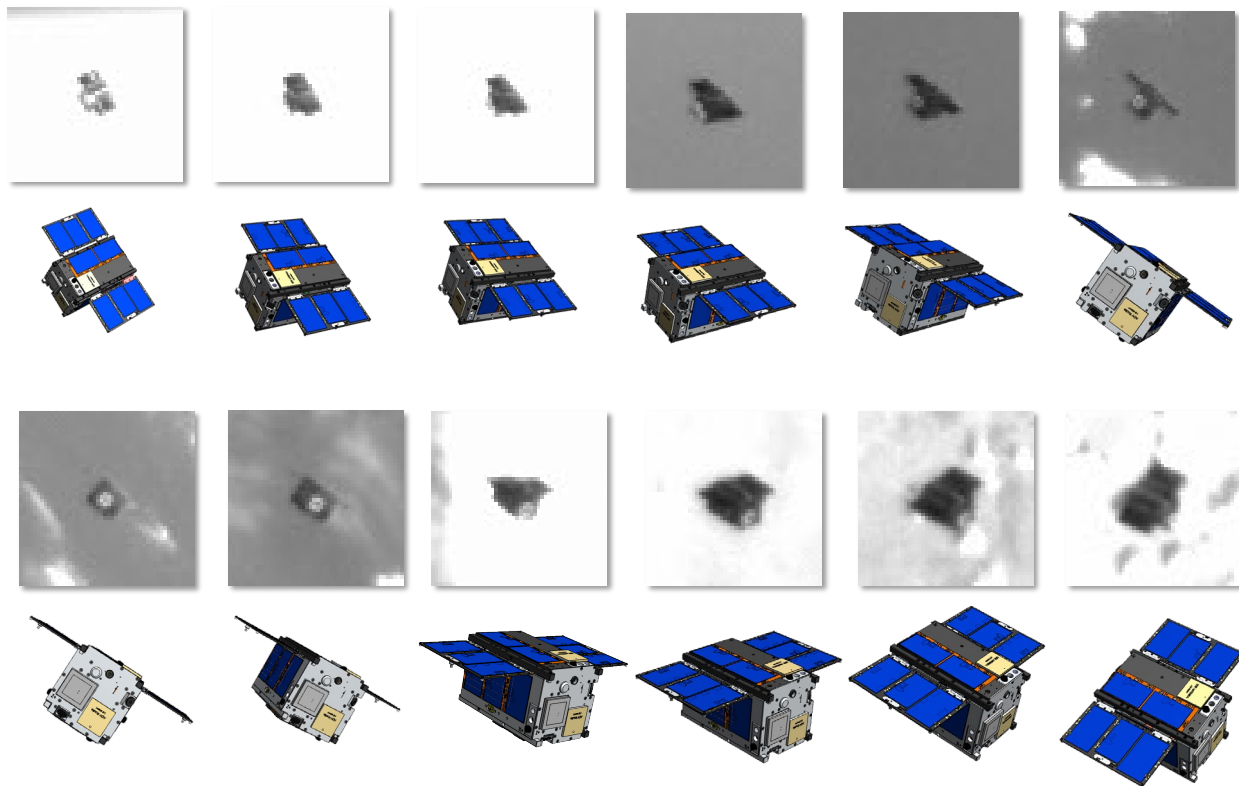
Figure 10. Composite of all 12 inspection images of AC10A captured by AC10B on 17 June 2020.

optimally illuminated satellite would have been lost in the darker features of the terrain.

Lastly, keeping AC10A in the frame throughout the collection was foiled by ephemeris uncertainty. In the case of AeroCube-10, the inherent level of uncertainty in the vehicles' GPS fixes and the need to propagate states several hours into the future yielded enough in-track error to drive AC10A out of the frame late in the collection, when the satellites were closest and the line of sight perpendicular to the in-track direction. The evolution of the NMCs on 16 and 17 June was driven primarily by differential drag, which is difficult to model accurately due to uncertainty in the atmospheric density and in the ballistic coefficients of the two vehicles. In the lead-up to an inspection activity, the timing of close approaches sometimes shifted by tens of minutes after incorporating a small amount of additional navigation data that improved knowledge of drag behavior, even though both AeroCube-10 vehicles are nearly identical. In the case of a dedicated inspection vehicle in proximity to a larger target, the uncertainty in cross-sectional area and mass properties may dominate the execution of the inspection over the state knowledge itself. Consequently, an inspection mission that demands high probability of success will likely require on-board (and autonomous) target

detection and tracking capabilities that maintain the target in frame in a closed-loop fashion without depending on relative state determination or propagation.

CLOSE APPROACH #3: 1 JULY 2020

The third inspection attempt occurred at the beginning of July 2020. Out-of-plane maneuvers reduced the cross-track and radial spiral motion of AC10B relative to AC10A to a 15 x 20 m ellipse, which remained passively safe. The operations team elected to have AC10B pass by AC10A with maneuver-induced motion, the behavior of which can be predicted more accurately than when relying on differential drag, but at the expense in this case of a shorter period of drifting NMCs. Figure 11 shows plots of the intersatellite range during the close approach and the solar phase angle of AC10A (i.e., the AC10B-AC10A-Sun angle), where low values have the Sun at the back of AC10B and are ideal for imaging.

For the selected close approach on 1 July 2020, the closest expected range was approximately 20 m. Similar to the inspection activity in June, operators planned to collect a series of images over 34 minutes as the vehicles' range varied from greatest to closest. The series yielded 10 high-quality images.
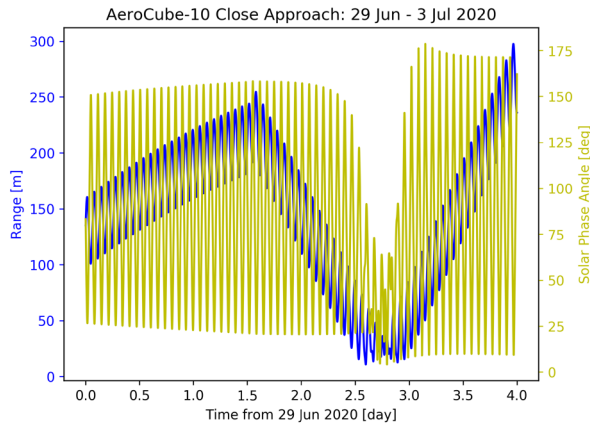
Figure 11. Relative range between the AeroCube-10 vehicles and the solar phase angle of AC10A around the 1 July 2020 close approach.

Figure 12 shows one of the first images, which has a space background and some Earth horizon in the lower right that is obscured by the inset. At a range of 30.8 m, features as small as 1 cm are distinguishable on AC10A. Six solar cells, three on the bus and three on a solar-panel wing, stand out as dark rectangles against the surface. A bright patch on one face of the bus corresponds to the satellite's radiation dosimeter, a secondary payload. And on the visible small face of the bus is the atmospheric probe magazine.

The image captured closest to AC10A appears in Figure 13 from a range of 21.8 m, providing a resolution of 0.8 cm. Unfortunately, the visible faces of the bus and solar panel wings are comparatively featureless, but at this resolution not only are the individual solar cells visible but also the harnessing between them.

Resolution ~ 1.1 cm

Latitude = 39.7 N, Longitude = 135.0 E
Range = 30.8 meters
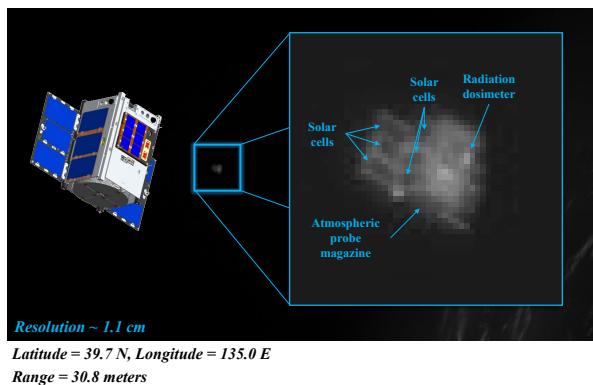
Figure 12. An image of AC10A captured by AC10B on 1 July 2020 at 20:40:05.08z at a range of 30.8 m. The image has a resolution of 1.1 cm and many features on AC10A are visible, including solar cells, the radiation dosimeter, and the atmospheric probe magazine.

Figure 13 also illustrates the challenge described earlier of keeping the target in the frame during an inspection run. At a range of ~22 m, the long axis of the 29 deg FOV spans less than 10 m, which is well within the expected in-track error bounds. Preparation of the inspection activity's open-loop pointing plan requires using navigation data from previous downlinks and

Resolution ~ 0.8 cm
Latitude = 51.5 N, Longitude = 174.1 E
Range = 21.8 meters
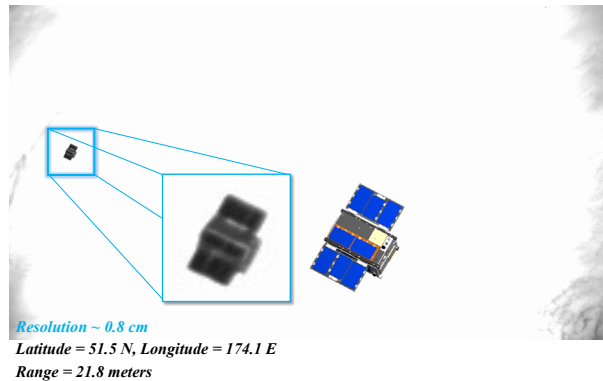
Figure 13. Image of AC10A captured by AC10B on 1 July 2020 at 20:48:05.12z at a range of 21.8 m. The resolution of features on AC10A is 0.8 cm. The cloudy Earth is overexposed in the background.

then propagating several hours into the future. Our experience flying more than 20 AeroCube satellites has shown that propagation error can grow by as much as 100 m per day from epoch, and keeping the satellite in a 10-meter-wide FOV at closest approach after 2-4 hours of propagation is at the limit of what one can expect to accomplish with the AeroCube-10 architecture as-is. The ~11 deg offset of AC10A from the center of the frame in Figure 13 suggests the ephemeris error at the time was 4-5 meters.

The challenge of inspection at closest approach is also compounded by the relative orbit geometry. At closest approach, AC10B is roughly along the radial line with respect to AC10A, so the dominating in-track ephemeris error is perpendicular to the line of sight. Consequently, the location of greatest interest for inspection imagery is also the location with the highest probability of the target falling out of the FOV. In contrast, at the furthest range in the NMC, AC10B looks roughly along the in-track direction, and although in-track errors may affect the range at which the target appears in the frame, capture within the frame is less likely to be affected.
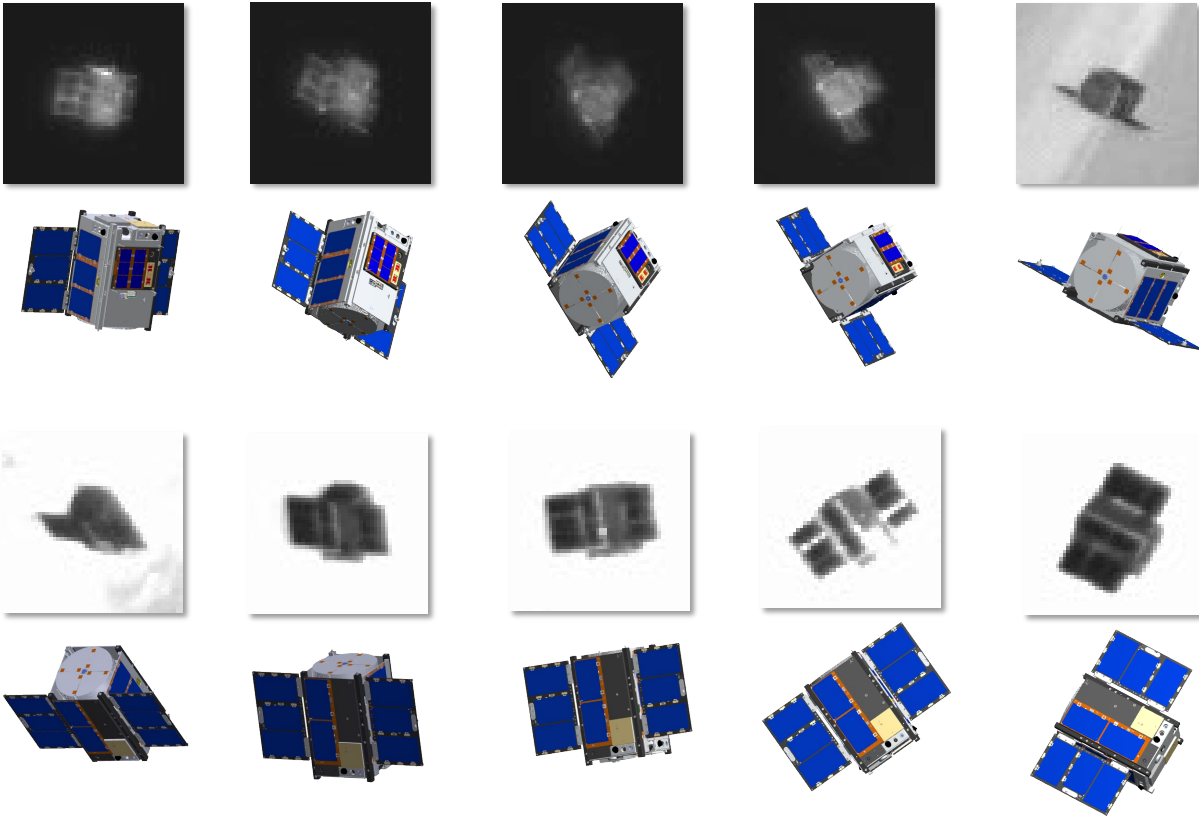
Figure 14. Composite of all 10 inspection images of AC10A captured by AC10B on 1 July 2020.

The full set of 10 inspection images from 1 July 2020, cropped to the target AC10A, appears in Figure 14. At the top left, the series begins at a range of 31.8 m, and the series concludes at bottom right at a range of 21.8 m. As with the inspection run in June, AC10A was left to tumble during the exercise, but in this case all six faces of the satellite were observed.

The first image in the top right has the distinct bright highlight on the small face of the bus from the GPS patch antenna (see Figure 9). The images in the top row also prominently capture the small face of the bus that includes the atmospheric probe magazine, which creates a circular silhouette against the rectangular bus outline. For comparison, a photo of the as-flown -Z face of AC10A, including the probe magazine, appears in Figure 15. The stowed probes are largely featureless and made of black anodized aluminum. They do not stand out in Figure 14 against the bus, even in good lighting conditions.

The second half of the inspection images in the bottom row capture the back broadside of AC10A, the bus face with a communications patch antenna and solar cells and the two solar panel wings with their easily distinguished individual solar cells.

DISCUSSION AND CONCLUSION

AeroCube-10 and its operations team succeeded in demonstrating that a vehicle as small as 1.5U has the capacity to perform extremely close proximity operations and an inspection mission safely and despite myriad limitations and operational constraints inherent in the satellites' design, which was never envisioned to perform such pathfinding activities.
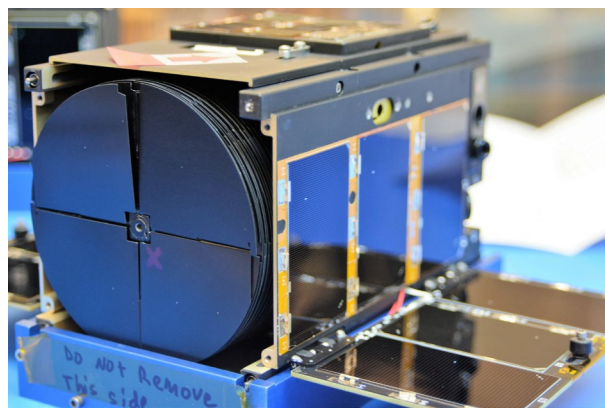
Figure 15. The -Z face of AC10A and the atmospheric probe magazine.

Because AeroCube-10 is a technology demonstration mission, limitations on the subsystems' capabilities were expected, and some of the operational constraints described in this paper have since been overcome for other AeroCubes. For example, the star trackers, which flew for the first time on AeroCube-10 as an experiment, have been upgraded to ensure reliable operation in both eclipsed and daylit portions of an orbit and are now operating on follow-on satellites in orbit. Also, AC10B's camera was not selected for its suitability to captured resolved imagery of another satellite in close proximity, but other Aerospace CubeSats have flown and are flying cameras that would provide substantially improved resolution and clarity and that would still fit in the 1.5U form factor.

Two upgrades to the AeroCube architecture related to relative navigation and autonomy will ensure more reliable inspection activities in the future. First, on-board GPS-data processing and orbit determination will substantially improve the pointing accuracy on an observing vehicle, and even more so if the vehicles are acting cooperatively and can share orbit state information in real time via crosslink. Aerospace has been developing flight software for real-time OD processing and deployed a prototype on AeroCube-10. The prototype has shown great promise for future missions that cannot tolerate the error inherent in hours-long propagations from the ground. Furthermore, the AeroCube-10 GPSR currently collects both L1 and L2 signals, and future iterations of the unit will incorporate the L2 signal into navigation fixes, which should increase the precision of the fixes by a factor of ~5.

Second, autonomous tracking algorithms (coupled with appropriate sensors) will be essential to overcome the challenges associated with tracking an inspection target and keeping it in frame. AeroCube-10's purely open-loop demonstration was always at the mercy of ephemeris- and pointing-uncertainty statistics. However, in non-cooperative scenarios, improvements in ephemeris and other uncertainties will only go so far to ameliorate the problem, and closed-loop tracking with on-board processing will be the most reliable way to ensure success of an inspection activity. Indeed, improvements in navigation uncertainty may be unnecessary if the inspection can initialize in a location where the probability of initial acquisition is high, such as when the observer-to-target line of sight is aligned with the in-track direction.

Many applications for on-orbit inspection envision scenarios where an inspector provides diagnostic information about a primary object, such as a high-value asset or a large piece of debris, or about a secondary object in the vicinity of a primary. In these circumstances, the capability for a primary vehicle to carry its own inspectors with it—and to deploy and exploit them on demand—may be essential. However, inspector concepts that are 6U, 12U, or larger are unlikely to meet this need without imposing a substantial size, weight, and power penalty on its host. A primary host vehicle could carry multiple 1.5U inspector CubeSats in one or more of various commercially available dispensers and release them on an as-needed basis. Such vehicles must reliably maneuver back to the host (or transfer to another object of interest in or near the same orbit) and collect imagery via proximity operations in a manner that is passively safe to all objects involved. Where diagnostic needs are modest but agility and flexibility are paramount, AeroCube-10 has demonstrated that solutions as small as 1.5U that provide these capabilities are well within the realm of the possible.

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