

Operations, Orbit Determination, and Formation Control of the AeroCube-4 CubeSats

Joseph W. Gangestad, Brian S. Hardy, and David A. Hinkley
 The Aerospace Corporation
 2310 E. El Segundo Blvd, El Segundo, CA, 90245; 310-336-3995
 joseph.gangestad@aero.org

ABSTRACT

Three satellites of the AeroCube-4 series built by The Aerospace Corporation were launched in September 2012 from Vandenberg Air Force Base. These satellites were each equipped with an on-board GPS receiver that provided position measurements with a precision of 20 meters and enabled the generation of ephemerides with meter-level accuracy. Each AeroCube was also equipped with two extendable wings that altered the satellite's cross-sectional area by a factor of three. In conjunction with the GPS measurements, high-precision orbit determination detected deliberate changes in the AeroCube's drag profile via wing manipulation. The AeroCube operations team succeeded in using this variable drag to re-order the satellites' in-track configuration. A differential cross-section was created by closing the wings of one satellite while the others' remained open, and the relative in-track motion between two AeroCubes was reversed. Over the course of several weeks, the satellites' in-track configuration was re-ordered, demonstrating the feasibility of CubeSat formation flight via differential drag.

INTRODUCTION

Since 1999, The Aerospace Corporation (Aerospace) has launched 16 small satellites and 4 reentry breakup recorders. Over the course of the Aerospace picosatellite program, the growing demands of picosatellite applications has driven the development of increasingly sophisticated small-satellite hardware and software and the implementation of systems-engineering techniques that facilitate turnover of approximately one mission per year.

The three CubeSats of the AeroCube-4 series built by The Aerospace Corporation were launched aboard an Atlas V launch vehicle from Vandenberg Air Force Base on 13 September 2012. These three 1U CubeSats were secondary payloads with eight other CubeSats, deployed from the OUTSat module [1]. All CubeSats were delivered to a roughly 480 x 780 km altitude orbit inclined at 65 deg.

The satellites of the AeroCube-4 series are designated in this paper as AC4-A, AC4-B, and AC4-C. Table 1 shows the relationship between these monikers and their numbers in the Space Object Catalog maintained by the Joint Space Operations Center (JSpOC). The mass of each satellite is approximately 1.2 kg.

Table 1. AeroCube-4 Names and Catalog Numbers

Name	NORAD Catalog #
AC4-A	38767
AC4-B	38768
AC4-C	38769

The mission of the AeroCube-4 series required sophisticated attitude knowledge and control for precise pointing of the AeroCubes and ground-based facilities [2], a challenge that demanded high-precision knowledge of the satellites' state in space. High-precision orbit determination (OD) was made possible by a GPS receiver installed on each satellite that collected fixes on a regular basis and delivered measurements of the satellites' position and velocity.

In addition to the standard 10-cm cube-shaped bus, all three AeroCube-4 satellites are equipped with extendable wings (9 x 10 cm), as depicted in Figure 1. Deployment or retraction of the pair of wings on command alters the cross-sectional area of each AeroCube by up to a factor of three. During the course of the mission, the operations team successfully deployed and retracted the wings on all three CubeSats.

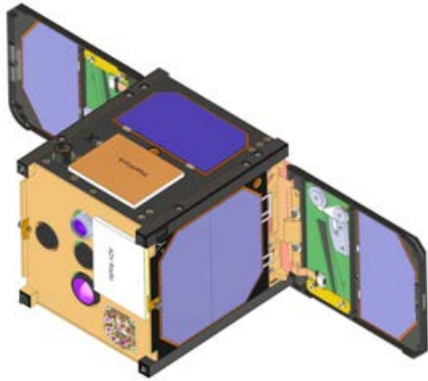


Figure 1. AeroCube-4 with extended wings.

This paper reports on the operations activities for the AeroCube-4 program, from September 2012 through the summer of 2013, including the successful utilization of the on-board GPS receiver, high-precision orbit determination for GPS validation and mission operations, detection of deliberate ballistic-coefficient variation, and formation control.

ORBIT ESTIMATION

Most CubeSat programs rely on two-line element sets (TLEs) released to the public by the JSpOC to determine their orbit and plan communication passes. TLEs for the OUTSat CubeSats have been issued approximately daily on the JSpOC-maintained website SpaceDataSource.¹

In addition to the TLEs, GPS fixes permitted our team to cooperate with the JSpOC in locating and tracking the AeroCubes, particularly during the early-orbit phase of the mission when differentiation between the eleven OUTSat CubeSats was problematic and TLEs could only be released at irregular intervals.

GPS Fixes

The GPS receiver aboard the AeroCube-4 series was designed and built at The Aerospace Corporation based on a terrestrial Software Defined Radio receiver that was ported for space applications. The least-squares navigation algorithm originally written for terrestrial application remains unchanged, which causes slight degradation in accuracy. The satellite-selection and

signal-reacquisition strategy were designed specifically for a tumbling CubeSat's sporadic reception (when not performing specific mission-related pointing, the satellites were left to tumble). During development, a Spirent GPS simulator was used for functional verification.

When a run of GPS fixes is requested by the operator, the GPS receiver queries for three fixes in short succession (within a few seconds of each other), and repeats that nine times in approximately ten-minute increments, yielding a maximum 27 fixes, with these nine sets of three evenly spaced over the orbit. Unfavorable spacecraft attitude for the GPS antenna may yield fewer than 27 for a particular run.

Typically the GPS receiver is commanded to acquire fixes once a day, depending on power budget and operational priority. Acquiring fixes every orbit would be impractical for data-storage and power reasons. Since launch, the AeroCube-4 satellites have returned thousands of GPS fixes, each averaging approximately 16 per day. Figure 2 shows a time history of the GPS fixes downlinked from AC4-B and -C through April 2013. (AC4-A failed early in its mission and few GPS fixes were acquired.)

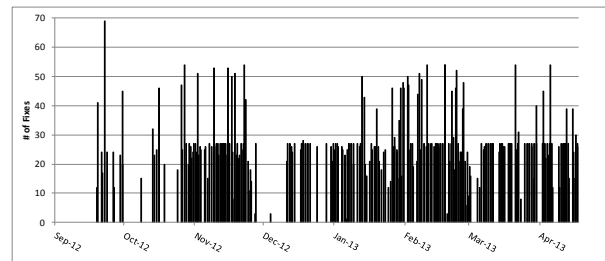


Figure 2. Time history of GPS fixes from AC4-B and -C through April 2013.

GPS fixes are processed on board the AeroCube and received in binary form through the radio downlink. After conversion to an ASCII format, the GPS fix contains several elements: the time of the fix (precise to the millisecond), the latitude, longitude, and altitude of the satellite, the velocity of the satellite in Earth-fixed Cartesian coordinates, and estimates of the fix's Position Dilution of Precision (PDOP), Time Dilution of Precision (TDOP), and Time To First Fix (TTFF). Conversion from GPS time to UTC time is done on board, including a post-launch software update to account for the June 2012 leap second. Only fixes with PDOP and TDOP less than 6 were retained for purposes of orbit determination.

¹ The JSpOC has approved an Orbital Data Request submitted by The Aerospace Corporation to disseminate the TLE-derived analyses presented in this paper.

Comparison of GPS fixes and TLEs

An important validation for the AeroCube's on-board GPS receiver was a comparison to the TLEs issued by the JSpOC. Most day-to-day operations for the AeroCube use TLEs (e.g., for ground-station pointing), and it was desirable to obtain an estimate of the time horizon over which a TLE would remain viable for our operations. The OUTSat TLEs are issued only once per day and not on Sundays or holidays; a long holiday weekend could see as much as a three day gap between TLEs.

Figure 3 shows the in-track, cross-track, and radial differences for AC4-B between the GPS fixes, which with their 20-meter uncertainty are treated as "truth," and TLEs propagated with the SGP-4 algorithm [3]. Each AC4-B TLE was propagated with SGP-4 to the epoch of all its GPS fixes (up to a maximum of 10 days) and the position difference calculated (after conversion of the TLE and GPS states to the same reference frame and coordinate system). The position difference was then converted to in-track, cross-track, and radial components. This process was repeated for each TLE available for AC4-B.

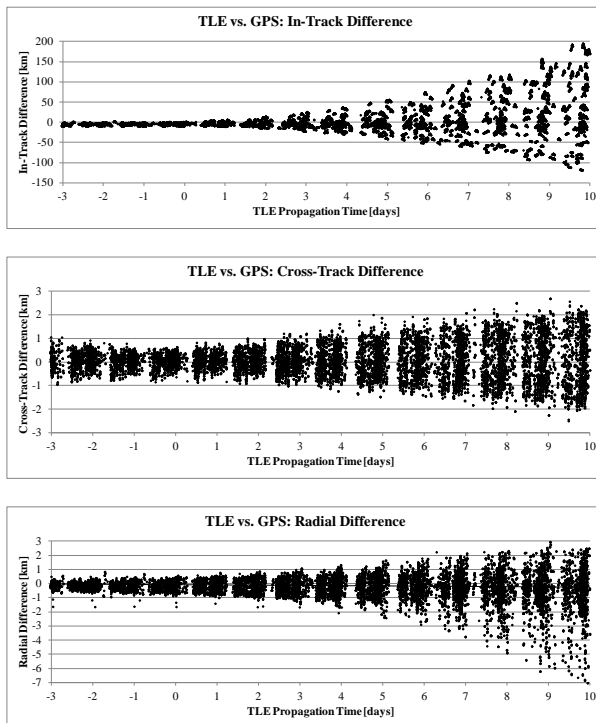


Figure 3. The in-track, cross-track, and radial differences between the AC4-B GPS fixes and SGP-4 propagated TLEs.

The envelope of in-track difference grows in an approximately quadratic manner at a rate of 10–20 km

per day. Much of this error is attributable to the SGP-4 model, which is limited to a gravity model with terms up to J_4 and a power-function atmosphere model. Uncertainties in the issued TLE elements and the time-variable drag profile of AC4-B (as it nominally tumbles when not tasked to point precisely) also contribute. The difference propagated in negative time is smaller because the TLEs are created by fitting past data.

The distribution of in-track differences is not symmetrical about zero; on average, the TLE places AC4-B "ahead of" the GPS state more often than behind. This effect is most likely caused by discrepancies in the atmosphere model and drag profile. If the SGP-4 atmosphere model over-estimates the true particle density, the satellite would "fall" more quickly, increasing its mean motion and pulling ahead of the "true" GPS-based state.

The cross-track differences, which represent knowledge of the orbit plane's orientation, do not exceed 3 km after 10 days of propagation. The rate of growth is similar to the radial differences: 1 to 3 km over the 10 days of propagation.

The envelope of radial differences, which are considerably smaller than in-track, are mostly constant over the 10-day span of propagation, growing from approximately from 1 to 3 km. The bias at 7–10 days in favor of a negative radial difference (down to as much as -7 km) is again symptomatic of the atmosphere model discrepancies: if AC4-B is falling more quickly than the GPS-based state, its radial position will by definition appear lower.

Orbit Determination and GPS Precision

The orbit-determination tool used in the AeroCube program is TRACE, a software program developed by The Aerospace Corporation and used throughout industry, with a nearly 50-year legacy of use in orbital analysis and spacecraft operations [4].

For orbit propagation, TRACE uses a force model with optional levels of fidelity, depending on input. For all propagations and orbit determination performed for this study, the models used in TRACE were:

- 1) Earth gravity: 70 x 70 Earth Gravitational Model 1996 (EGM96)
- 2) Atmospheric drag: Mass Spectrometer Incoherent Scatter model 1986 (MISIS-86) with time-varying solar flux and geomagnetic indices.
- 3) Third-body perturbations: Moon and Sun point-mass gravity

- 4) Solar radiation pressure (SRP) with flat-plate assumption, including eclipsing

TRACE performs orbit determination with a batch-filter algorithm, using the propagation model to find a best-fit solution that minimizes the residuals between the propagated state and the input measurements (for this study, Earth-fixed coordinates from the GPS fixes). Covariance is evaluated separately with a sequential algorithm that incorporates the measurements chronologically. At the end of an orbit-determination run, the TRACE solution contains eight numbers: the best-fit initial state (position and velocity vectors), the best-fit ballistic coefficient, and the best-fit coefficient for SRP. TRACE also outputs the 1-sigma uncertainty for each.

Before mission operations could rely on GPS-based ephemerides, it was necessary to determine the precision of the GPS fixes. Although the GPS receiver calculates the PDOP and TDOP of each fix, no reliable method exists that can translate the dilution of precision to an uncertainty in meters. At the start of the mission, the exact uncertainty of the measurements from the GPS receivers was unknown, although it had been estimated to the order of tens of meters at worst.

At the end of each OD run, TRACE makes available the root-mean-square (RMS) of the measurement residuals weighted by the measurements' *a priori* uncertainty. If the OD run is successful, the residuals should be on the order of the measurement uncertainty, and this weighted RMS should be close to unity. When on-orbit GPS fixes became available, we used the weighted RMS output from TRACE as a means to ascertain the measurements' uncertainty. Over several different OD runs with the same data, we tuned the *a priori* covariance until the weighted RMS was close to unity. Runs with several different sets of data showed that the measurement uncertainty was constant over time, making it unnecessary to tune for each OD run.

This tuning process identified the 1-sigma measurement uncertainties as 40 meters for AC4-A and 20 meters for AC4-B and AC4-C. The source of the larger uncertainty for AC4-A is unknown, but we suspect that it is related to other anomalies on the spacecraft that later led to its failure. Few GPS fixes were collected from AC4-A, and a characterization of its GPS receiver was left incomplete.

Example Orbit Covariance

A typical OD run incorporates three to six days of GPS fixes. Beyond that time span, the gaps in the propagation model—such as any un-modeled atmospheric variability and the time-varying ballistic

coefficient of the AeroCube—create undesirable residuals in the final solution.

An example OD run was performed for 17–23 April 2013, during which time 212 GPS fixes were collected in 6 batches. A guess for the initial state is created with a TLE. After several iterations, the batch algorithm converged on a best-fit solution and output both a multi-day ephemeris and the associated covariance at each time step of the ephemeris. The converged initial state was within a few kilometers of the TLE-based guess. The covariance is evaluated independently of the batch filter using a sequential algorithm that starts with an initial estimate of the covariance (usually large) and then uses subsequent measurements to reduce the state uncertainty. Figure 4 shows plots of the in-track, cross-track, and radial uncertainty of this example OD run, as extracted from TRACE's output covariance.

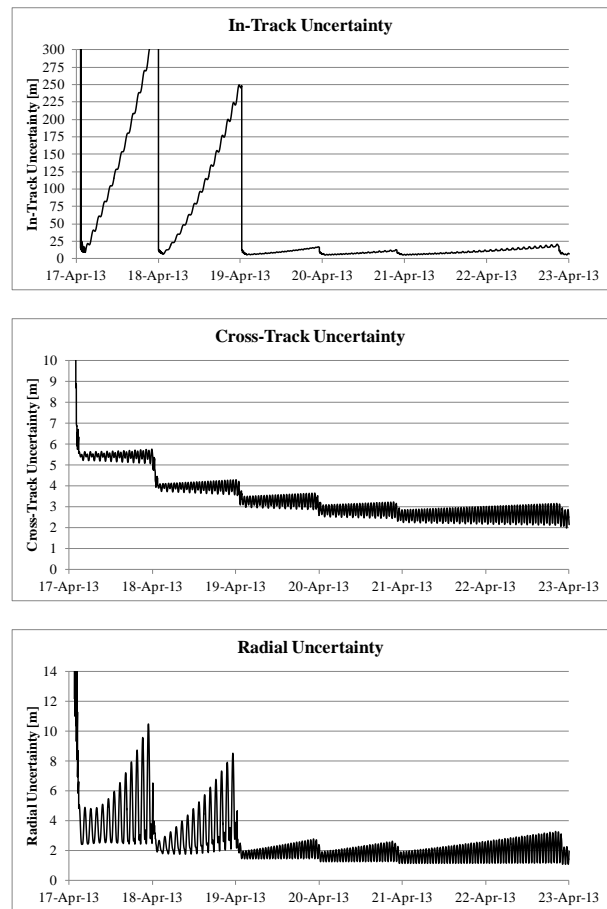


Figure 4. In-track, cross-track, and radial state uncertainty for an example OD run in TRACE, extracted from TRACE's output covariance. The discontinuous drops in uncertainty correspond to sets of GPS fixes entering the solution.

The initial input covariance for all three directions was 10 km, which is off the scale of these plots. This large number is necessary to ensure that the batch algorithm has enough freedom during the OD process to converge on the correct state. Each discontinuous drop in the plotted uncertainty corresponds to the introduction of new GPS fixes into the covariance.

After three sets of GPS fixes (i.e., by 19 April), the in-track uncertainty drops below 25 meters, with a growth rate of approximately 8 meters per day. Subsequent fixes on 20, 21, and 23 April keep the in-track error below 25 meters throughout the propagation period after 19 April.

The cross-track uncertainty is reduced with every set of GPS fixes, down to as low as 3 meters with the last fixes (around 22 April). The radial uncertainty is also reduced to 2 meters or less after the first few sets of fixes. Both have low error-growth rates; instead, the covariance oscillates by approximately 1 meter about the mean.

Based on the results of many other OD runs performed during the course of the mission, the operations team began to require three sets of GPS fixes spaced over two or three days as the minimum for generation of a high-precision ephemeris.

Timescales of Ephemeris Quality

In order to obtain an ephemeris with precision better than that available from a TLE, a GPS-based ephemeris could be generated with TRACE by propagating the best-fit OD solution with the same high-fidelity model. For planning purposes, these ephemerides would be required several days in advance, but it was unclear how the quality (i.e., precision) of the GPS-based ephemerides changed over time or how they compared to TLE-based ephemerides at the same epoch.

Three timescales were selected to investigate the ephemeris quality: a reference time T_0 , at which the highest quality ephemeris would be needed for operations, T-3 days, and T-14 days. For each epoch, a GPS-based ephemeris was created by using an OD solution with 3–4 days of GPS fixes leading up to that epoch (e.g., at T-3 days, fixes from T-6 to T-3 days were used). A TLE-based ephemeris used the TLE closest to (but not after) the epoch. All of these ephemerides were extended by propagation (high-fidelity TRACE propagation for the GPS ephemerides and SGP-4 for TLEs) through T_0+2 days, yielding a 2-day “evaluation period” relative to T_0 in which the in-track, cross-track, and radial errors could be compared. The GPS-based ephemeris at T_0 was used as the “truth” ephemeris on account of the known meter-level

covariance from the OD solution (whereas TLEs are uncertain to 1–3 km at epoch).

Several cases were run for different T_0 in January and February 2013, evaluating the in-track, cross-track, and radial differences between GPS- and TLE-based ephemerides at T-14 days and T-3 days. A summary of the average position errors appears in Table 2.

Table 2. Position Error Relative to the GPS-based Ephemeris at T_0

Ephemeris	Avg. In-Track Difference [km]	Avg. Cross-Track Difference [km]	Avg. Radial Difference [km]
TLE @ T-14	135	3.5	3.2
GPS @ T-14	54	0.1	0.6
TLE @ T-3	11	1.9	1.3
GPS @ T-3	3	0.01	0.05
TLE @ T_0	4	1.1	0.9

Using GPS fixes 14–17 days old and propagating through T_0 , the GPS-based ephemeris has an average in-track error of approximately 54 km relative to the ephemeris based on the freshest fixes before T_0 . The GPS ephemeris from T-3 days has an in-track error of approximately 3 km relative to T_0 . Although the GPS-based ephemerides are considered “high fidelity,” the challenges of long-term propagation are immediately apparent from Table 2: even with measurements precise to 20 meters and a slowly growing covariance, the imperfect prediction of future conditions in the model can lead to substantially different future behavior and several kilometers of error.

The cross-track and radial errors in GPS-based ephemerides are very small, even 14 and 3 days out from T_0 . The most unpredictable model in the propagation (i.e., the atmosphere) does not contribute to out-of-plane perturbations, which manifest in cross-track errors, so the GPS-based ephemerides are reliable in the cross-track direction before T_0 . Similarly, the average radial error is also small, only 0.6 km at T-14 days; although the in-track and radial errors are linked (for the same reason as the asymmetric bias in the GPS vs. TLE analysis above), only a small radial error is necessary to induce the in-track errors seen in Table 2, especially over a 14-day propagation.

The performance of the TLE-based ephemerides in Table 2 is poorer than GPS. At T-14 days and T-3 days, the GPS-based ephemeris outperforms by approximately a factor of 3 in the in-track direction and an order of magnitude (or more) in cross-track and radial. The low-fidelity model of the SGP-4 propagator inherently limits the cross-track and radial performance

of the TLE-based ephemerides to the ~1-km precision evident in Table 2, and the SGP-4 atmosphere model further contributes to poor propagation on a 14-day timescale.

FORMATION CONTROL

Ballistic Coefficient Control

During the early-orbit and checkout phases of the AC4-B mission in November 2012, the CubeSat’s wings were opened and closed to verify their functionality. These tests provided the opportunity to detect a change in the satellite’s ballistic coefficient, a key parameter that must be controllable for any mission that requires formation control.

Changes in ballistic coefficient could be detected through the variability of orbital elements (primarily through the semimajor axis), but the low drag at the AeroCube’s 480 x 780 km altitude orbit would require weeks to unambiguously detect an effect (see next section). Instead, it was desired to detect a wing change as quickly as possible—preferably a few days—via high-precision GPS measurements.

On 14 November 2012 at 02:10 UTC, the wings of AC4-B were closed. Over the next three days, AC4-B collected 77 GPS fixes in 4 batches (approximately 1 set of 20 fixes every day). On 17 November at 05:00 UTC, the wings were opened, after which another 103 fixes were collected in 4 days.

Orbit determination was performed on these fixes, extending from 14–21 November. The OD model included a discontinuous change in ballistic coefficient at the time the wings were opened, and the solution provided two best-fit ballistic coefficients: one while the wings were closed, and one while open.

Table 3 summarizes the results from the orbit determination, showing the ballistic coefficient and 1-sigma uncertainty across the open-close event of AC4-B’s wings. While the wings were closed, the best-fit ballistic coefficient from the OD was found to be $423.3 \pm 0.4 \text{ cm}^2/\text{kg}$; after the wings were opened—increasing the cross-sectional area of the satellite—the best-fit ballistic coefficient increased by approximately 35%, to $574.8 \pm 0.4 \text{ cm}^2/\text{kg}$.

Table 3. Wing-Induced Change in Ballistic Coefficient

Event	Ballistic Coefficient [cm ² /kg]
Wings closed	423.3 ± 0.4
Wings open	574.8 ± 0.4

During both wing-closed and wing-open phases the satellite was tumbling, and the ballistic coefficients in Table 3 serve best as an approximation or long-term average of the time-varying drag profile. Because of this time-variability and the uncertainty in the ballistic coefficient between the two configurations [5] [6], it is not meaningful to convert the ballistic coefficients into cross-sectional areas. However, the 35% increase in the best-fit ballistic coefficient is strong evidence that GPS fixes in conjunction with high-fidelity orbit determination are adequate to detect changes in drag profile over a short time frame and independently from on-board telemetry.

Formation Re-phasing

In late November 2012, one of the last commands issued to AC4-A was to close its wings. By that time, the formation of all three AeroCubes had spread out in the in-track direction, in the order AC4-B, -A, and -C from trailing to leading. Closing the wings would decrease the rate of altitude loss on AC4-A so that, in time, AC4-B (with wings open and hence a larger drag profile) would fall below -A, and their relative positions would switch (i.e., AC4-B, falling lower and with a higher mean motion, would catch up with and pass AC4-A), marking the AeroCube program’s demonstration of deliberate formation control.

Contact with AC4-A was lost shortly after the wing-close command was issued, and GPS fixes after the event were unavailable to verify the closure. Instead, it became necessary to track the progress of AC4-A through TLEs.

Figure 5 shows a plot of the in-track angular separation between the three AeroCube-4 satellites from the start of mission through April 2013. Plotting the angular separation (as opposed to in-track distance) is necessary because the satellites drifted so far apart that the linear approximation of the standard in-track, cross-track, and radial coordinate system breaks down. In this figure, if the angular separation is positive, then the first satellite in each label is “ahead” of the second in the label.

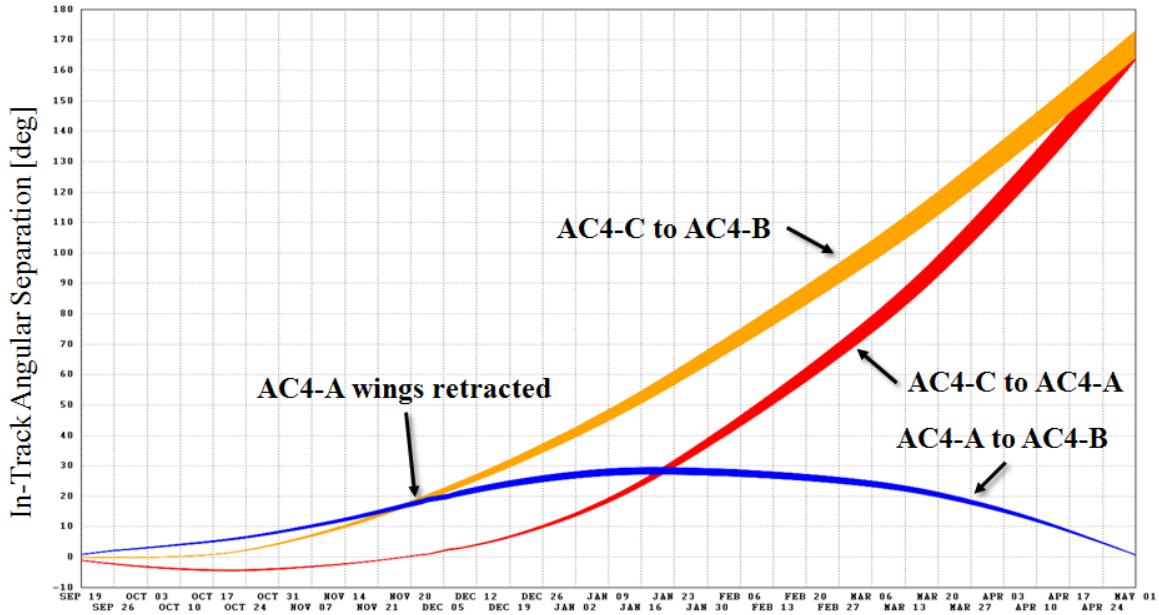


Figure 5. In-track angular separation of the three AeroCube-4 satellites through April 2013. The separation between AC4-A and AC4-B shows a turnaround related to the deliberate reconfiguration of the constellation by altering AC4-A's drag profile.

Starting in December 2012 the rate of in-track separation between AC4-A and -B decreases, and the in-track separation reaches a maximum in mid-January 2013. For the rest of 2013, the separation between AC4-A and -B decreases, indicating that AC4-B is “catching up” with AC4-A. This change in relative motion would occur only if the mean motions of the two satellites had diverged. In particular, the reversal of relative motion in December 2012 requires AC4-B to have fallen below AC4-A, which would have occurred only if the differential drag on AC4-B were higher. This behavior indicates that the wings of AC4-A did indeed close and that the goal of deliberate formation control via differential drag was successful.

For further verification of the change in AC4-A's behavior, Figure 6 shows a plot of the orbit periods of the three AeroCube-4 satellites from the start of mission through April 2013, as derived from the TLEs. (These orbital elements are evaluated at the TLE epoch, which corresponds to the satellites' ascending-node crossing.)

Except for brief tests, the wings of AC4-B and -C were open throughout the course of the mission. Having the same drag profile, the time histories of both satellites' orbit period have nearly the same slope: they experience nearly the same orbit-averaged drag force and therefore “fall” at nearly the same rate. (The absolute difference in orbit period is due to the initial deployment dispersions at the start of the mission.)

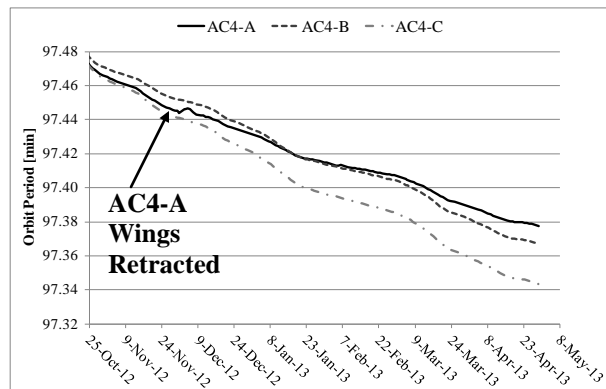


Figure 6. Orbit period of the three AeroCube-4 satellites, as measured from the TLEs at epoch, through April 2013.

However, AC4-A shows a change in slope compared to the others starting in late November 2012, after its wings were closed, and the slope remains less steep throughout the time frame plotted. In late January 2013, the orbit periods of AC4-A and AC4-B became equal, corresponding to the peak of in-track separation in Figure 5. Thereafter, the orbit period of AC4-A remained higher than both AC4-B and -C, allowing AC4-B to gain ground on AC4-A, which eventually led to AC4-A and -B switching places in the constellation's in-track configuration on 2 May 2013.

CONCLUSIONS

The AeroCube-4 series of three satellites have provided a wealth of experience in the operation of a CubeSat constellation that will be invaluable for future missions that require sophisticated formation flying with multiple small spacecraft [7]. With the aid of an on-board GPS receiver, the AeroCube-4 series of three satellites has successfully demonstrated the ability to produce high-precision ephemerides for a CubeSat with meter-level uncertainty and subsequently use this orbit-determination capability to independently detect commanded changes in the satellites' drag profile. By deliberately closing the wings of one satellite, the operations team succeeded in reducing its rate of descent, thereby reconfiguring the in-track formation of satellites and demonstrating the feasibility of CubeSat formation flight via differential drag.

ACKNOWLEDGMENTS

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