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

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AeroCube-4
Three-Satellite Constellation

Orbit:
450 x 750 km
65 deg inclined

3 ground stations in US

Launched on 13 September 2012

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AeroCube-4 GPS Fixes

*Comparison to TLEs*

- GPS Receiver logs 27 fixes evenly spaced over an orbit.
- Compare GPS-based position fix vs. TLE-prediction position:

- TLE envelope of difference from GPS grows by ~15 km per day
Orbit Determination
High-Fidelity, High-Precision Orbit Knowledge

• Precision of fixes:
  – Position: ~20 m
  – Velocity: ~1 m/s

• Orbit determination:
  – Feed fixes into TRACE, Aerospace’s high-fidelity orbit-determination software
    • Batch least-squares algorithm for orbit estimation + sequential filter for covariance analysis
  – Output new ephemeris based on high-fidelity model

• Covariance analysis:
  – After 5 sets of fixes, position uncertainty < 10 m
Ballistic-Coefficient Control

Wings Closed – Wings Open

Solving for the best-fit ballistic coefficients, orbit determination detected the wing-open event after a few days of GPS fixes.
AeroCube-4 Orbit Decay

Orbit Period vs. Time

AC4-A began to fall more slowly when its wings were closed.

AC4-B and -C, whose wings are open, have a comparable decay rate.
Closing the wings of AC4-A reversed the direction of in-track separation growth. Eventually the positions of AC4-A and AC4-B switched as desired.
Summary

- AeroCube-4 successfully deployed on orbit. Operating for 11 months and still going strong.
- GPS receivers return fixes precise to 20 m, and high-fidelity orbit determination does still better.
- Capable of detecting drag profile changes when wings open or close.
- Successfully re-ordered in-track configuration of constellation via differential drag.

*Building skills for the future:* AeroCube-7, with laser comm and proximity ops
Appendix
GPS Receiver

*CubeSat Orbit Determination*

- Receiver designed and built at The Aerospace Corporation
  - *Based on a terrestrial Software Defined Radio receiver ported for space applications*
  - *Least-squares navigation algorithm*
  - *Satellite-selection and signal-reacquisition strategy designed for tumbling CubeSat’s sporadic reception*
- **Operation:**
  - *Receiver queries for three fixes in short succession (within a few seconds)*
  - *Repeats query 9 times spaced ten minutes apart*
  - *Result: ~27 fixes spaced evenly over the orbit*
- **Precision**
  - *Position: ~20 m*
  - *Velocity: ~1 m/s*
GPS Fixes, AC4-B and -C

Continuous collection through summer 2013

Collected >4000 fixes from each satellite. Average 17–18 fixes per day.
GPS Fixes vs. TLEs – In-Track

Growth of TLE Differences in Time

TLE envelope of difference from GPS grows by ~15 km per day
GPS Fixes vs. TLEs – Cross-Track and Radial

Growth of TLE Differences in Time

**TLE vs. GPS: Cross-Track Difference**

**TLE vs. GPS: Radial Difference**
## Timescales of Ephemeris Quality

**TLE vs. GPS over a Fortnight**

<table>
<thead>
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<tbody>
<tr>
<td>TLE @ T-14</td>
<td>135</td>
<td>3.5</td>
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<td>GPS @ T-14</td>
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<tr>
<td>TLE @ T₀</td>
<td>4</td>
<td>1.1</td>
<td>0.9</td>
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AeroCube-4 Semimajor Axis

Semimajor Axis vs. Time

![Graph of AeroCube-4 Semimajor Axis](image-url)
AeroCube-4 Orbit Period

Orbit Period vs. Time

AeroCube-4—Orbit Period

97.48
97.46
97.44
97.42
97.40
97.38
97.36
97.34
97.32
97.30

Orbit Period [min]

25-Nov-12
24-Nov-12
24-Dec-12
8-Jan-13
7-Feb-13
22-Feb-13
9-Mar-13
24-Mar-13
8-Apr-13
23-Apr-13
8-May-13
23-May-13
7-Jun-13
22-Jun-13
22-Jul-13
6-Aug-13

AC4-A
AC4-B
AC4-C
AeroCube-4 Inclination

Inclination vs. Time

![AeroCube-4—Inclination Graph](image-url)
AeroCube-4 Apogee Altitude

Apogee Altitude vs. Time
AeroCube-4 Perigee Altitude

Perigee Altitude vs. Time

![Graph showing AeroCube-4 Perigee Altitude vs. Time]

- AC4-A
- AC4-B
- AC4-C
AeroCube-4 Eccentricity

Eccentricity vs. Time