DRIFT RECOVERY AND STATION KEEPING RESULTS FOR THE HISTORIC CANX-4/CANX-5 FORMATION FLYING MISSION

23rd Annual Frank J. Redd Student Competition

Josh Newman
CanX-4&5 Mission Overview

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of spacecraft</td>
<td>2</td>
</tr>
<tr>
<td>Wet mass</td>
<td>6.5 kg</td>
</tr>
<tr>
<td>Size</td>
<td>20x20x20 cm</td>
</tr>
<tr>
<td>$I_{sp}$</td>
<td>40 s</td>
</tr>
<tr>
<td>Total $\Delta V$</td>
<td>15 m/s</td>
</tr>
</tbody>
</table>

**Payloads:**
- CNAPS cold-gas thruster
- GPS receiver
- Inter-Satellite Link (ISL)
Formation Flying

• Two Formation Types
  1. Along-Track Orbit
  2. Projected Circular Orbit
Chapter I

THE CHALLENGE
~ 100 km/day
Drift Recovery Context

• Bring the spacecraft close
  - (a few km)

• Reduce relative motion
  - (a few cm/s)

• **Fuel efficiently**
  - (a few m/s)

• Easily extendable to include station keeping
  - (< a few headaches)
Chapter II

FORMULATING A SOLUTION
Drift Recovery and Station Keeping Overview
Mission architecture

- Chief/Deputy

- Chief – passive, is the reference trajectory by definition

- Deputy – active, manoeuvres to create, maintain, and leave formations

- State: \( s_d = s_c + \delta s \)
Gauss’ Variational Equations

\[\begin{align*}
da &= \frac{2a^2}{\sqrt{\mu a(1-e^2)}} \left[ e \sin \theta \Delta V_R + (1 + e \cos \theta) \Delta V_{AT} \right] \\
d\epsilon &= \sqrt{\frac{a(1-e^2)}{\mu}} \left[ \sin \theta \Delta V_R + \frac{2 \cos \theta + e(1 + \cos^2 \theta)}{(1 + e \cos \theta)} \Delta V_{AT} \right] \\
di &= \sqrt{\frac{a(1-e^2)}{\mu} \cos(\omega + \theta)} \crn{\epsilon} \Delta V_Z \\
d\Omega &= \sqrt{\frac{a(1-e^2)}{\mu} \sin(\omega + \theta)} \sin i \frac{\Delta V_Z}{(1 + e \cos \theta)} \\
d\omega &= \sqrt{\frac{a(1-e^2)}{\mu} \left[ \frac{-\cos \theta}{e} \Delta V_R + \frac{(2 + e \cos \theta) \sin \theta}{e(1 + e \cos \theta)} \Delta V_{AT} - \sin(\omega + \theta) \tan i \frac{\Delta V_Z}{(1 + e \cos \theta)} \right]} \end{align*}\]
Drifting Elements

RAAN
Eccentricity
Argument of Perigee
Mean Anomaly

- Drifts due to non-spherical shape of the Earth.
- Makes the chief a moving, spiraling, oscillating target
Game Plan

1. Arrest the spacecraft drift

2. Create the opposite drift, back together

3. Phase the periodic motions

4. At the target range, stop relative motion
Trajectory Optimization

• Most important and most complicated part of the drift recovery sequence

Minimize:

\[
\Delta V_{cost} = \Delta V_{Trajectory} + \Delta V_{Ecc/ArgP} + \Delta V_{Stop} + \Delta V_{Time}
\]
\[ \Delta V_{\text{cost}} = \Delta V_{\text{Trajectory}} + \Delta V_{\text{Ecc/ArgP}} + \Delta V_{\text{Stop}} + \Delta V_{\text{Time}} \]

The fuel cost, measured in m/s, of a specific trajectory. This is the cost we want to minimize.
\[ \Delta V_{\text{cost}} = \Delta V_{\text{Trajectory}} + \Delta V_{Ecc/ArgP} + \Delta V_{\text{Stop}} + \Delta V_{\text{Time}} \]

The fuel cost to go from the initial state, with the spacecraft moving apart, to one where the spacecraft are moving back together

Primary goal: change $a$, $i$,
Secondary goal: correct $e$, $\omega$
Trajectory Optimization

\[ \Delta V_{\text{cost}} = \Delta V_{\text{Trajectory}} + \Delta V_{\text{Ecc/ArgP}} + \Delta V_{\text{Stop}} + \Delta V_{\text{Time}} \]

The fuel cost to correct the eccentricity and argument of perigee.

Changes: \( e, \omega \)
Trajectory Optimization

\[ \Delta V_{\text{cost}} = \Delta V_{\text{Trajectory}} + \Delta V_{\text{Ecc/ArgP}} + \Delta V_{\text{Stop}} + \Delta V_{\text{Time}} \]

The fuel cost to bring the relative semi-major axis and inclination to zero when the spacecraft rendezvous

Changes: \( a, i \)
Trajectory Optimization

\[ \Delta V_{\text{cost}} = \Delta V_{\text{Trajectory}} + \Delta V_{\text{Ecc/ArgP}} + \Delta V_{\text{Stop}} + \Delta V_{\text{Time}} \]

The value that is applied to time, in m/s.

Typically, the fuel leak rate is used.
Testing

• Thousands of simulations, varying:
  - Deployment geometry
  - Attitude control
  - Navigational errors
  - Delays in commissioning

• Tested on spacecraft hardware simulator

• Algorithms robust against initial conditions and control errors

• Total confidence in mission success
Chapter III

ON-ORBIT RESULTS
Launch

- Launched 30 June 2014 aboard PSLV-C23
- 650 km, circular, sun-synchronous
- Ejected from separate deployment systems
Cumulative Impulse and Range during Drift Recovery

- Propulsion system commissioning and calibration
- Faster recovery trajectory
- Deceleration into stationkeeping
- Eccentricity and argument of perigee correction
- Recovery trajectory

Graph showing cumulative impulse delivered and relative formation range from 1 July to 30 August.
Drift Recovery Summary

• 18 July to 2 September 2014
• Maximum separation: 2320 km
• Final separation: 2.95 km

• 102 individual manoeuvres commanded
• ΔV: 2.03 m/s

• Another 1\textsuperscript{st} on the nanosatellite scale
Station Keeping Summary

- 02 September to 19 November 2014
- 59 manoeuvres
- 0.81 m/s
Passive Collision Avoidance

Actual On-Orbit Data

At 2:26 on 3 November, the final formation completes
Where we are and What’s Next?

- Primary mission objectives completed in November 2014

- Currently in safe-hold mode, 125 km apart.

- Hopeful to acquire funding to perform further testing, but nothing final yet
Thanks!

ANY QUESTIONS?
Special Thanks

- My family
- Grant Bonin, Niels Roth, Scott Armitage, Ben Risi
- Brad Cotten, Thomas Sears, Jamie Fine, John Chung
- SFL Community
- Dr. Robert E. Zee
Orbital Mechanics 101

Keplerian two-body equation of motion:

**Acceleration:**
\[
\ddot{\mathbf{r}} = -\frac{\mu \mathbf{r}}{|\mathbf{r}|^3}
\]

**Position:**
\[
r = \frac{a(1-e^2)}{1+e \cos \theta}
\]

**Velocity**
\[
\dot{r} = \sqrt{\mu \left(\frac{2}{r} - \frac{1}{a}\right)}
\]

Where \(a\) is semi-major axis, \(e\) is eccentricity, \(\theta\) is true anomaly, and \(\mu\) is the gravitational parameter of the primary body (Earth).
Drifting Elements

Mean Anomaly

• Drifts secularly as a function of semi-major axis, due to non-spherical shape of the Earth.
  – Two spacecraft in similar orbits but different semi-major axes will drift apart without bound.
  – Two spacecraft in similar orbits but separated along-track can be brought together over time by changing their relative semi-major axes.

• For given separation and relative semi-major axis, the time to intersection can be found.
Drifting Elements

RAAN

- Drifts secularly as a function of semi-major axis and inclination.
  \[
  \frac{d\Omega}{dt} = -\frac{3}{2} \frac{J_2 R_\oplus^2}{(1 - e^2)^2} \sqrt{\frac{\mu}{a^7}} \cos i
  \]

- Non-zero relative \(\Omega\) manifests as a periodic cross-track motion.

- Can be fixed instantaneously, or via relatively small changes in a, i over time.
Drifting Elements

Relative RAAN, Inclination, and Semi-Major Axis over Time

Date [UTC]
Drifting Elements

Argument of Perigee and Eccentricity

• For moderately low values of eccentricity, $\omega$ varies secularly:

\[
\dot{\omega} = \frac{1}{2} G \eta (1 - 5 \cos^2 i)
\]

\[
\eta = \sqrt{1 - e^2}
\]

\[
G = -\frac{3}{2} J_2 \left( \frac{R_\oplus}{a \eta^2} \right)^2
\]

• $e$ oscillates about a mean point
Drifting Elements

Mean Argument of Perigee and Eccentricity - Eccentricity not Very Low

Days

Eccentricity

Mean Argument of Perigee

Mean Eccentricity

Argument of Perigee [°]

0.0095

0.01

0.0105

0.011

0.0115

0.012

0.0125

0

60

120

180

240

300

360

0 20 40 60 80 100 120
Drifting Elements

Argument of Perigee and Eccentricity

• For very low values of eccentricity, $\omega$ oscillates about $90^\circ$
Propagator Configuration
DRASTK GUI

[Image of DRASTK GUI interface]

- Ephemeris Files & Initialization
  - Chief * e file
  - Deputy * e file
  - Output Directory

- Drift Recovery Planning
  - Drift Recovery Window Start (UTC)
  - Stage
    - 1 - Return Trajectory and Onward
    - 2 - Eccentricity/Argument of Perigee Thrusts and Onward
    - 3 - Rendezvous
  - Create Recovery Plan

- Drift Recovery Execution
  - Recovery Plan File
  - Stage
    - 1 - Return Trajectory
    - 2 - Course Correction
    - 3 - Eccentricity/Argument of Perigee Thrusts
    - 4 - Rendezvous
    - 5 - Post-Rendezvous Station Keeping
    - 6 - Station Keeping with Passive Safety
    - 7 - Drift Arrival
  - Create Thrust Commands

- Depleted Relative State
  - SMA (km)
  - Inclination (deg)
  - Eccentricity
  - RAAN (deg)
  - Arg of Perigee (deg)
  - Mean Anomaly (deg)
  - Range (km)
  - Epoch (UTC)

- Configuration
  - Spacecraft
    - Coefficient of Drag
    - Deputy Drag Area (m^2)
    - Chief Drag Area (m^2)
    - Fuel Mass (g)
    - Wet Mass (g)
    - Loss Rate (mph)
  - Engine
    - Isp (s)
    - Thrust Per Nozzle (N)
    - Max Impulse per Thrust (Ns)
    - Minimum Impulse Bit (Ns)
  - Gravity Model
    - Degree
    - Order
  - Rendezvous & Station Keeping
    - Days Between Control Thrusts
    - Passive Safety (m)
DRASTK Plan File

<table>
<thead>
<tr>
<th>Drift Recovery Plan</th>
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<tbody>
<tr>
<td>Date Created (local):</td>
<td>7/6/2014 20:27</td>
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<tr>
<td>Date of Return Trajectory Burn:</td>
<td>27 Jul 2014 17:25:45.000 UTCG</td>
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<tr>
<td>Target Relative SMA (km):</td>
<td>0.384</td>
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<tr>
<td>Target Relative Inc (deg):</td>
<td>0.001382573</td>
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<tr>
<td>Estimated DV (m/s):</td>
<td>0.764614191</td>
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<tr>
<td>Date of Ecc/ArgP Correction Burn:</td>
<td>5 Aug 2014 07:39:56.000 UTCG</td>
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<td>Estimated DV (m/s):</td>
<td>0.30571221</td>
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<tr>
<td>Date to Begin Rendezvous Burn:</td>
<td>18 Sep 2014 17:35:21.602 UTCG</td>
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<td>Relative range at Start of Rendezvous burn</td>
<td>167.3401463</td>
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<td>Days Taken to Rendezvous</td>
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<td>Rendezvous Time Constant</td>
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<td>Estimated DV (m/s):</td>
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<td>Total DV Spent on Manoeuvres (m/s)</td>
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<tr>
<td>Total DV Lost to Leakage (m/s)</td>
<td>0.629735117</td>
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<tr>
<td>Total DV spent on Drift Recovery (Leakage and Manoeuvres) (m/s)</td>
<td>2.026056032</td>
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<tr>
<td>Ecc/ArgPFlag</td>
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<tr>
<td>Initial Relative SMA</td>
<td>-0.756099255</td>
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<tr>
<td>Initial Relative Inc</td>
<td>-0.002140855</td>
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</table>
Trajectory Optimization

\[ \Delta V_{\text{cost}} = \Delta V_{\text{Trajectory}} + \Delta V_{\text{Ecc/ArgP}} + \Delta V_{\text{Stop}} + \Delta V_{\text{Time}} \]

The fuel cost to go from the initial state, with the spacecraft moving apart, to one where the spacecraft are moving back together

Change \( a \), to reverse secular along-track motion

\[ \frac{d\Omega}{dt} = -\frac{3}{2} \frac{J_2 R_\oplus^2}{(1 - e^2)^2} \sqrt{\frac{\mu}{a^7}} \cos i \]

Solution: change \( i \) at the same time
Trajectory Optimization

\[ \Delta V_{\text{cost}} = \Delta V_{\text{Trajectory}} + \Delta V_{\text{Ecc/ArgP}} + \Delta V_{\text{Stop}} + \Delta V_{\text{Time}} \]

\[
da = \frac{2a^2}{\sqrt{\mu a(1-e^2)}} [e \sin \theta \Delta V_R + (1 + e \cos \theta) \Delta V_{\text{AT}}]
\]

\[
d e = \sqrt{\frac{a(1-e^2)}{\mu}} \left[ \frac{\sin \theta \Delta V_R}{1 + e \cos \theta} + \frac{2 \cos \theta + e (1 + \cos^2 \theta)}{(1 + e \cos \theta)} \Delta V_{\text{AT}} \right]
\]

\[
d i = \sqrt{\frac{a(1-e^2)}{\mu}} \frac{\cos(\omega + \theta)}{1 + e \cos \theta} \Delta V_z
\]

\[
d \Omega = \sqrt{\frac{a(1-e^2)}{\mu}} \frac{\sin(\omega + \theta)}{\sin i (1 + e \cos \theta)} \Delta V_z
\]

\[
d \omega = \sqrt{\frac{a(1-e^2)}{\mu}} \left[ \frac{-\cos \theta}{e} \Delta V_R + \frac{2 + e \cos \theta \sin \theta}{e(1 + e \cos \theta)} \Delta V_{\text{AT}} - \frac{\sin(\omega + \theta)}{\tan i (1 + e \cos \theta)} \Delta V_z \right]
\]
Trajectory Optimization

Start

Get current state of each spacecraft

Choose a relative semi-major axis

Determine the combined fuel cost

Determine time to return

Determine the relative inclination needed to bring the relative RAAN to zero at return time
Trajectory Optimization

Relative RAAN, Inclination, and Semi-Major Axis over Time

- Relative Mean Inclination
- Relative Mean RAAN
- Relative Mean Semi-Major Axis

Date [UTC]

8-Dec  7-Jan  6-Feb  8-Mar

Relative RAAN and Inclination [°]

Relative Semi-Major Axis [km]
Trajectory Optimization

\[ \Delta V_{Ecc/ArgP} = \Delta V_{Ecc/ArgP_0} + S_{EccArgP} \Delta V_{AT,SMA} \]

where

\[ S_{Ecc} = -\left| \sin \left( 2\omega \frac{\pi}{2} + A \right) \right| \]

For CanX-4&5, \( A \sim 55^\circ \)
Ecc/ArgP Correction

\[ A = \sqrt{\frac{a(1-e^2)}{\mu}} \begin{bmatrix} 2 \cos \theta & \sin \theta \\ 2 \sin \theta & -\cos \theta \end{bmatrix} \]

\[ C = \begin{bmatrix} \Delta e \\ \Delta \omega \end{bmatrix} \]

\[ \Delta V_{Ecc/ArgP} = |A^{-1}C| \]

Find \( \theta \) such that \( \Delta V_{Ecc/ArgP} \) is minimized
Attitude Errors

Fuel Losses over Applied Attitude Control Error

- Return Trajectory Mean Fuel Loss
- Ecc/ArgP Mean Fuel Loss
- Return Trajectory Fuel Loss Standard Deviations
- Ecc/ArgP Fuel Loss Standard Deviations
- Mean Fuel Loss Best Fit
- Fuel Loss Standard Deviation Best Fit

26 August 2015
Josh Newman – 23rd Annual Frank J. Redd Student Competition
# Navigational Errors

<table>
<thead>
<tr>
<th>Gain</th>
<th>Position Error St. Dev. (m)</th>
<th>Absolute Velocity Error St. Dev. (mm/s)</th>
<th>Relative Velocity Error St. Dev. (mm/s)</th>
<th>Mean Fuel Error (%)</th>
<th>St. Dev. (pp)</th>
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<tbody>
<tr>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
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<td>15</td>
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<td>1.903</td>
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<td>17.83</td>
<td>11.97</td>
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<td>35</td>
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<td>4.489</td>
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<td>85</td>
<td>0.993</td>
<td>1.063</td>
<td>0.37</td>
<td>0.53</td>
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<tr>
<td>200</td>
<td>2.281</td>
<td>2.443</td>
<td>1.09</td>
<td>1.21</td>
<td></td>
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<tr>
<td>300</td>
<td>3.285</td>
<td>3.519</td>
<td>3.14</td>
<td>2.98</td>
<td></td>
</tr>
</tbody>
</table>
Passive Collision Avoidance

An unsafe relative orbit. If left uncorrected, these spacecraft will collide.
Combined errors

• Using 10 degree mean attitude error, absolute navigation error gain of 85 and relative navigation error of 15

• Expected fuel loss error of 5.75%, standard deviation of 2.80 pp

• $3\sigma$ fuel loss error is expected to be 14.15%
  - Within budget
Station Keeping

- Between autonomous formation flying experiments
- Keeps spacecraft safely separated
- Navigational errors, perturbations will cause the spacecraft to drift, possibly on a collision course
- Desire a passive state that will keep the spacecraft a safe minimum distance apart.
Passive Collision Avoidance

Passively safe (top) and unsafe (bottom) relative motion, as viewed from along the reference spacecraft's velocity vector.
Passive Collision Avoidance

1. Identify uncorrected radial, cross-track motions

2. Identify desired radial, cross-track motions

3. Find the intersections of the initial and desired states

4. Choose the intersection with the lowest relative velocity

5. Perform thrust
Passive Collision Avoidance

Perturbations - RAAN

• Recall:

\[
\frac{d\Omega}{dt} = -\frac{3}{2} \frac{J_2 R^2_\oplus}{(1 - e^2)^2} \sqrt{\frac{\mu}{a^7}} \cos i
\]

• Can cause cross-track motion to change over time, possibly creating a dangerous state
Passive Collision Avoidance

Perturbations - RAAN

• For a desired relative semi-major axis, an relative inclination can be found to negate the procession change

$$\Delta i_p = \cos^{-1}\left(\cos i_r \sqrt{\frac{a_r + \Delta a_p}{a_r}}^7\right) - i_r$$

$$\sqrt{\Delta i_p^2 + (\Delta \Omega_p \sin i_r)^2} = \sqrt{2} \frac{A_{safety}}{a_r}$$

$$\Delta i_p, \Delta \Omega_p \rightarrow z(0), \dot{z}(0)$$
Passive Collision Avoidance

Perturbations – Argument of Perigee

• To first order:

\[ \frac{d\omega}{dt} = -\frac{3}{2} \frac{J_2 R_\oplus^2}{(1 - e^2)^2} \sqrt{\frac{\mu}{a^7}} \left( 2 - \frac{5}{2} \sin^2 i \right) \]

• For CanX-4&5, -3.19 degrees/day
• Therefore, radial motion doesn’t have a period of 1 orbit, but actually 3.5 seconds shorter.
• Takes 112.8 days to complete one cycle
Passive Collision Avoidance

Perturbations – Argument of Perigee

• Therefore, if desired state is left for 56.4 days, at one point the cross-track and radial motions will line up. If the along-track distance crosses zero at that time, a collision will occur.
Passive Collision Avoidance

1. Identify uncorrected radial, cross-track motions

\[
\begin{align*}
\mathbf{x}(t) &= \begin{bmatrix} 4 - 3 \cos nt \\ 6 (\sin nt - nt) \\ 0 \\ 3n \sin nt \\ -6n(1 - \cos nt) \end{bmatrix} \\
y(t) &= \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \\
z(t) &= \begin{bmatrix} 0 \\ 0 \\ \cos nt \\ 0 \\ -n \sin nt \end{bmatrix} \\
\dot{x}(t) &= \begin{bmatrix} n^{-1} \sin nt \\ -2n^{-1}(1 - \cos nt) \\ 0 \\ \cos nt \\ -2 \sin nt \end{bmatrix} \\
\dot{y}(t) &= \begin{bmatrix} 2n^{-1}(1 - \cos nt) \\ n^{-1}(4 \sin nt - 3nt) \\ 0 \\ 2 \sin nt \\ 4 \cos nt - 3 \end{bmatrix} \\
\dot{z}(t) &= \begin{bmatrix} 0 \\ 0 \\ 0 \\ 2 \sin nt \\ 0 \end{bmatrix}
\end{align*}
\]

\[
\begin{array}{cccccc}
\text{Time [UTC]} & x [\text{km}] & y [\text{km}] & z [\text{km}] & v_x [\text{km/s}] & v_y [\text{km/s}] & v_z [\text{km/s}] \\
10/7/2014 4:00:00 AM & -0.016419 & 0.265132 & 0.029962 & -4.432 E-06 & 8.1179 E-05 & 1.3002 E-05
\end{array}
\]
Passive Collision Avoidance

Radial and Cross-Track Motion - Initial
2. Identify desired radial, cross-track motions

Radial and Cross-Track Motion

Position in LVH [km]

Time [UTC]
2. Identify desired radial, cross-track motions
Passive Collision Avoidance

3. Find the intersection(s) of the initial and desired state

Radial and Cross-Track Motion

![Graph showing radial and cross-track motion over time][1]

---

[1]: https://example.com/graph.png
Passive Collision Avoidance

4. Choose the intersection with the lowest relative velocity

<table>
<thead>
<tr>
<th></th>
<th>Intersection 1</th>
<th>Intersection 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time [UTC]</td>
<td>04:59:50</td>
<td>05:50:16</td>
</tr>
<tr>
<td>Radial displacement [m]</td>
<td>11.60</td>
<td>-14.83</td>
</tr>
<tr>
<td>Initial radial velocity [cm/s]</td>
<td>-0.6797</td>
<td>0.8338</td>
</tr>
<tr>
<td>Desired radial velocity [cm/s]</td>
<td>3.2598</td>
<td>-3.1055</td>
</tr>
<tr>
<td>Manoeuvre ΔV [cm/s]</td>
<td>-3.9395</td>
<td>3.9393</td>
</tr>
</tbody>
</table>
Commissioning

• Spacecraft both contacted within hours of launch

• Basic spacecraft health (power generation, temperatures) confirmed

• GPS and ISL systems validated within 24 hours
DRASTK Timeline

• Day 18 – “Dry run” zero-impulse thrust commands with inertial target attitudes executed.

• Day 19 – Following the success of the dry run, first real thrust performed

• Day 19-24 – Larger thrusts are performed, starting at 65 mNs up to the maximum 375 mNs.

• Day 28: on fuel-optimal return trajectory, 43 km/day
Drift Recovery

- Day 30: decision made to accelerate recovery (increase value of time in the cost function) to 105 km/day

- Day 45-46: Performed Ecc/ArgP correction thrusts

- Day 48: began deceleration from 320 km relative range

- Day 64: entered station keeping at 3 km relative range
Drift Recovery Manoeuvre Magnitudes by Frequency