A Small Spacecraft Swarm Deployment and Stationkeeping Strategy for Sun-Earth L1 Halo Orbits

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Background & Objective

Spacecraft orbits about the Sun-Earth libration point L1 have been of interest since the 1950s. An L1 halo orbit was first achieved with International Sun-Earth Explorer-3 (ISEE-3), and similar orbits around Sun-Earth L1 were achieved in the Solar and Heliospheric Observatory (SOHO), Wind, Advanced Composition Explorer (ACE), Genesis, and Deep Space Climate Observatory (DSCOVR) missions. These orbits are shown in Figure 1.

With recent advancements in cubesat technology, it will soon be feasible to deploy cubesats at L1. Compared to prior missions where one large satellite orbited alone, a swarm of cubesats enables novel science data return, providing a topology for intersatellite measurements of spatially and temporally varying heliophysics phenomena, with the ability to vary the intersatellite distances.

Our goal is to understand the 3D energy dissipation and turbulent structure of the solar wind. The mission concept is to deploy a swarm of eight cubesats from a modified powered ESPA ring, which itself has been inserted into a L1 Lissajous orbit. Strawman measurements are magnetometer data and radiometric measurements via the satellites' radio cross-links. This mission concept is illustrated in Figure 2. Mission objectives include:

1. Measuring the relative power in fluctuations parallel and perpendicular to the magnetic field
2. Determining whether or not the structure is time stationary, i.e. will we observe structures drift by the swarm, or observe the superposition of propagating waves?

Understanding ion-field coupling at the kinetic spatial scales (100km) is key to understanding the heating of the plasma by the magnetic field.

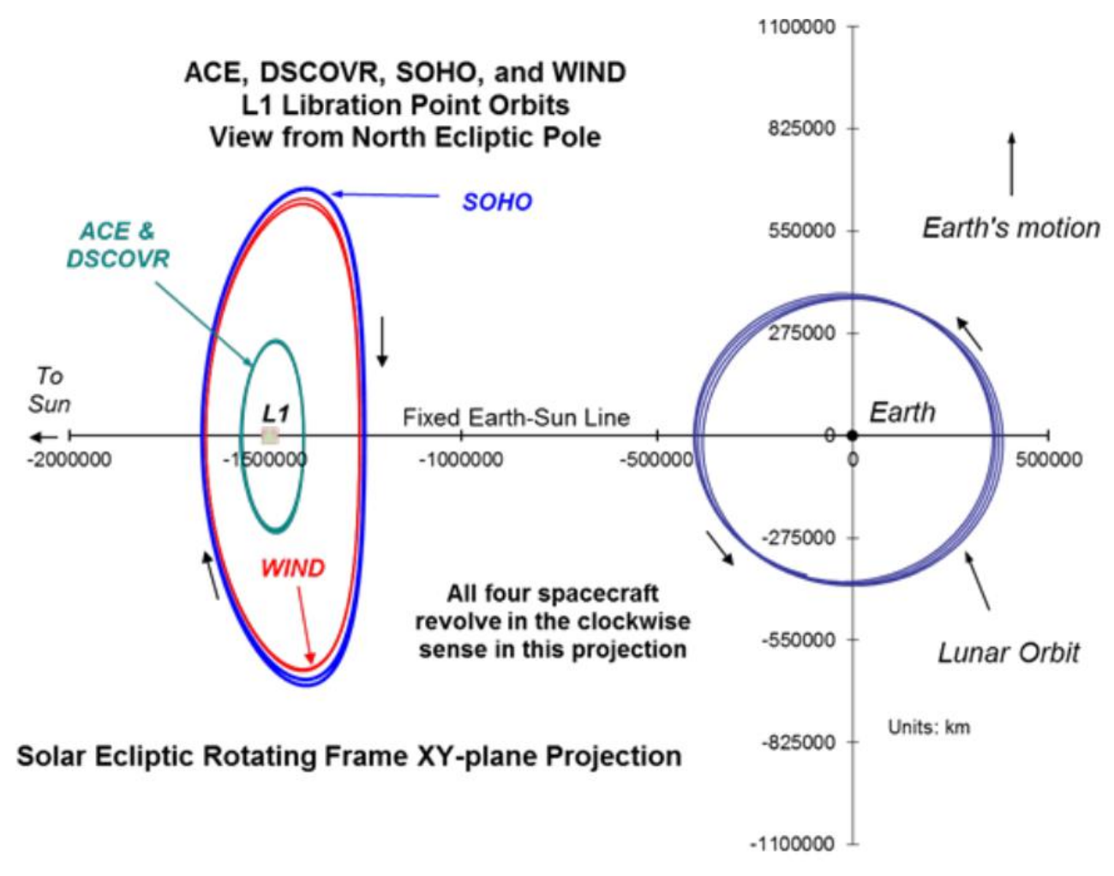


Figure 1: Past L1 mission orbits.[1]

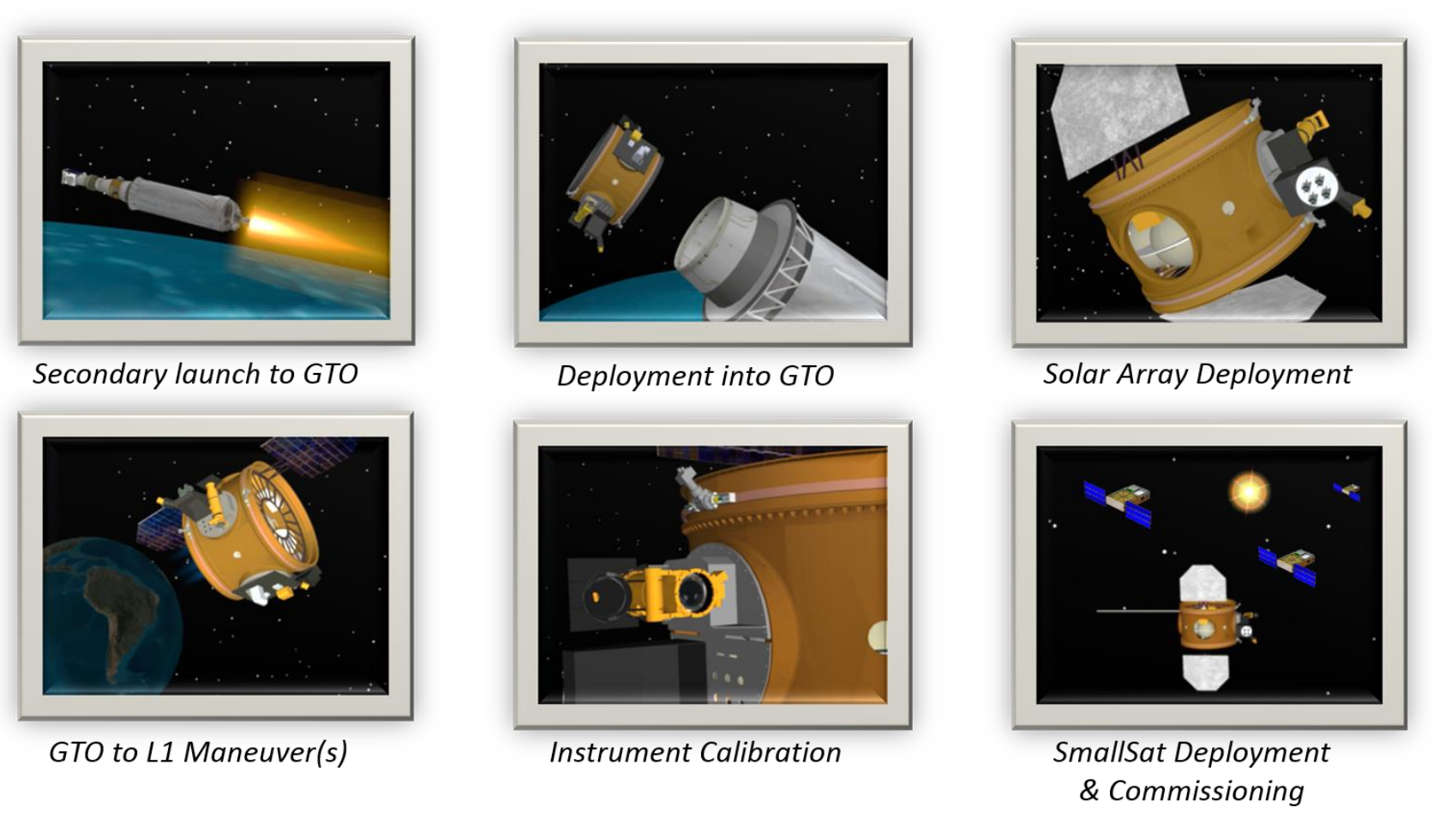


Figure 2. Heliophysics L1 mission sequence.

The objective of this study is to design and simulate a cubesat swarm control strategy for our L1 heliophysics mission concept that does not require ground-in-the-loop control for orbit maintenance. After deployment and an initial checkout phase, the science requirement for the next 30 days is to achieve ~10 km intersatellite baselines. After 30 days, the desired baselines would be time-varying. The long term evolution of the swarm will be addressed in a future study.

Method

Deployment

We assume the ESPA ring's initial condition to be a state vector from ACE's mission. Cubesat deployments are modeled as 1.2 m/s ejections from a dispenser, staged at 2 second intervals, in the ESPA's velocity vector direction (referenced in the ESPA's VNC frame). There is a four hour free drift phase, serving as a power-up and checkout phase. Afterwards, cubesats are maneuvered as needed to achieve the desired 10 km intersatellite baselines.

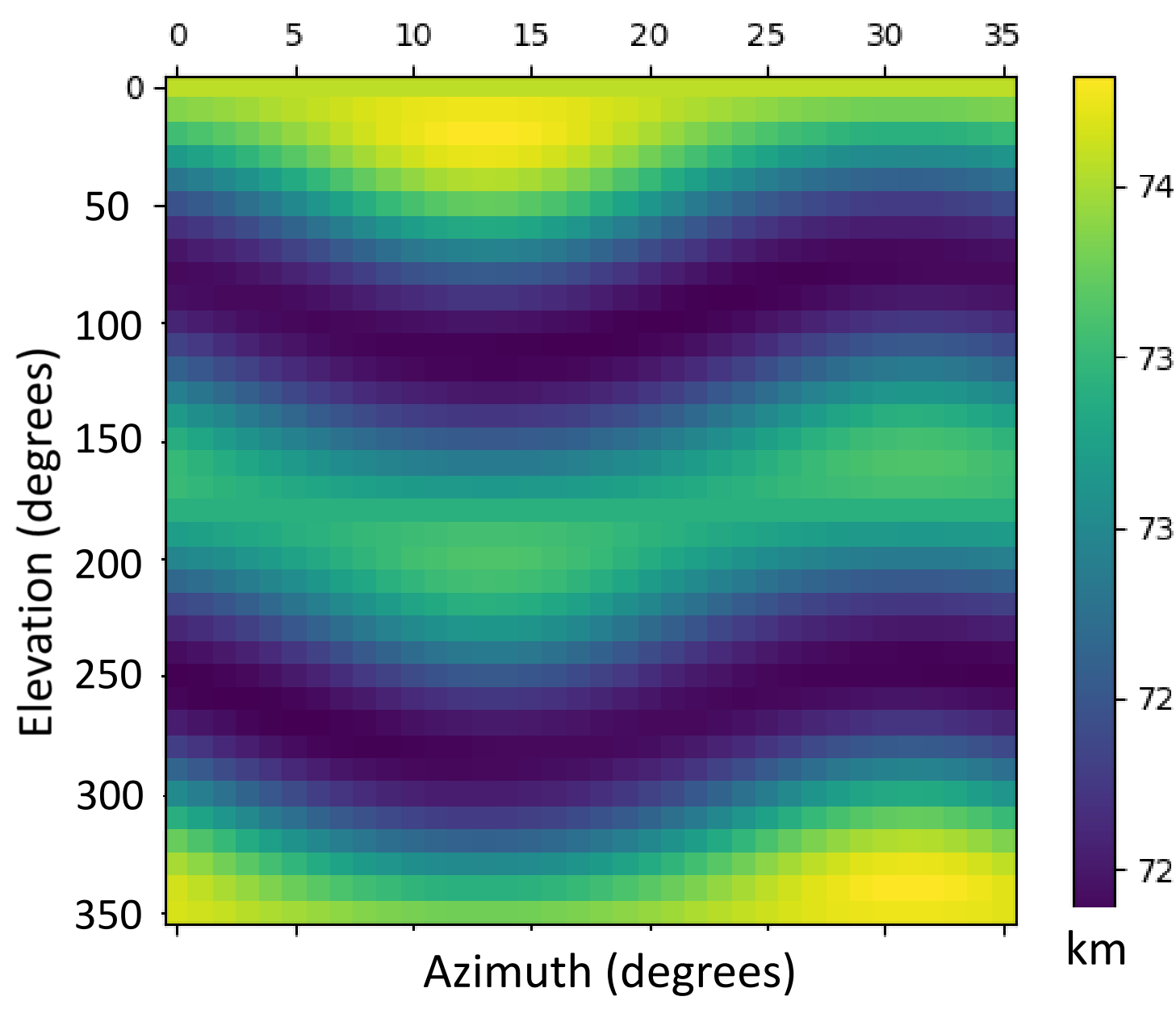


Figure 3. This figure illustrates all possible deployment vector directions in the ESPA rings's local-vertical, local-horizontal (LVLH) frame. Following seven days of free drift, the resulting separation distance (in km) is shown with the colormap. Without applied control, a cubesat deployed in any direction would separate over 700 km from the ESPA ring in just one week. This figure confirms the need for applied maneuvers to contain the swarm and prevent the their escape from L1.

Control Scheme

Our objective for the control technology is to develop an autonomous system, responsive to spacecraft position and velocity state estimates. We assume state data to be shared via the swarm's peer-to-peer network communication. Maneuvers will be autonomously determined onboard and implemented ***without ground intervention***.

To enable typical science mission durations that can exceed one year, control is implemented as a fuel-optimization solution. The multivariable vector $\overline{x}$ is defined as the three-axes components of $\Delta\overline{v}$ vectors for each of the eight cubesats, as well as a time horizon variable.

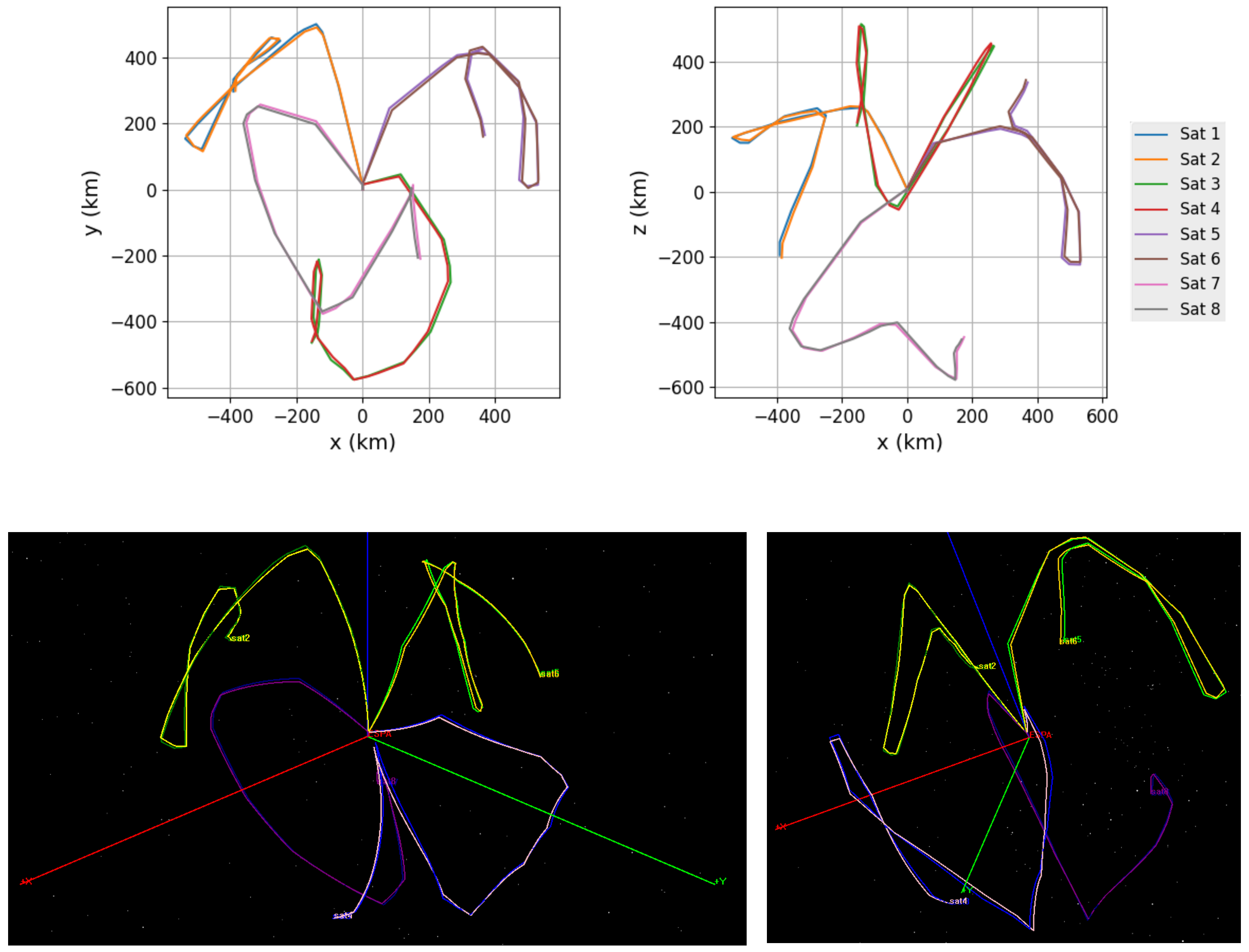
Software tools used for this analysis included `fmincon` from MATLAB's Optimization Toolbox[2], the General Mission Analysis Tool[3] (GMAT), and python[4].

At each iteration, `fmincon` was implemented as follows:

- The cost function to minimize is the sum of all prescribed $\Delta\overline{v}$ maneuvers
- Several nonlinear inequality constraints were defined:
  - Cubesats were constrained to drift no more than 650 km away from the ESPA ring. This represented a communication system constraint; the ESPA ring will act as a comm relay for transmitting data from the cubesats to Earth.
  - Components of the $\Delta\overline{v}$ vector were constrained to be representative of ***realistic cubesat propulsion systems***.
  - A keep-out zone of 2 km was assigned to each spacecraft to avoid collision risk
  - Four cubesat pairs were defined. Intersatellite distances between each pair, $\rho_{i,j}$, were constrained as: 9 km ≤ $\rho_{i,j}$ ≤ 11 km.
- For `fmincon` to compute the separation and intersatellite distances, GMAT was used to propagate the trajectories forward in time. GMAT's full ephemeris simulation included:
  - solar radiation pressure
  - gravity due to sun, Earth, and moon point masses
- A time horizon was defined as the time following the applied maneuvers in which the spacecraft must achieve the intersatellite baseline constraints. The time horizon was a variable that `fmincon` could optimize while finding a minimum fuel solution.

Results

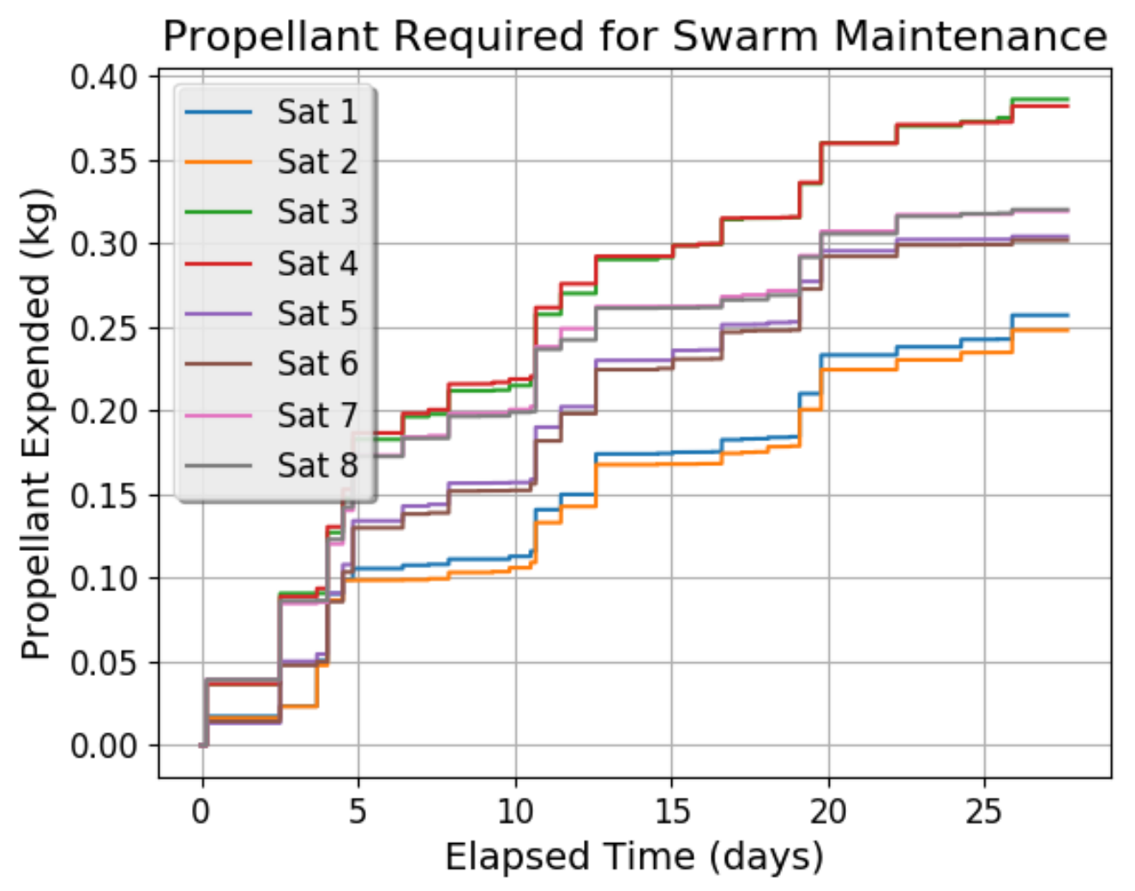
The mission sequence was simulated for the initial 30 day commissioning period, with the eight cubesat swarm completing 32 sets of maneuvers (256 total maneuvers). The resulting motion is shown in Figure 4, where the ESPA ring – itself orbiting L1 in a Lissajous orbit – serves as the origin of the frame of reference.

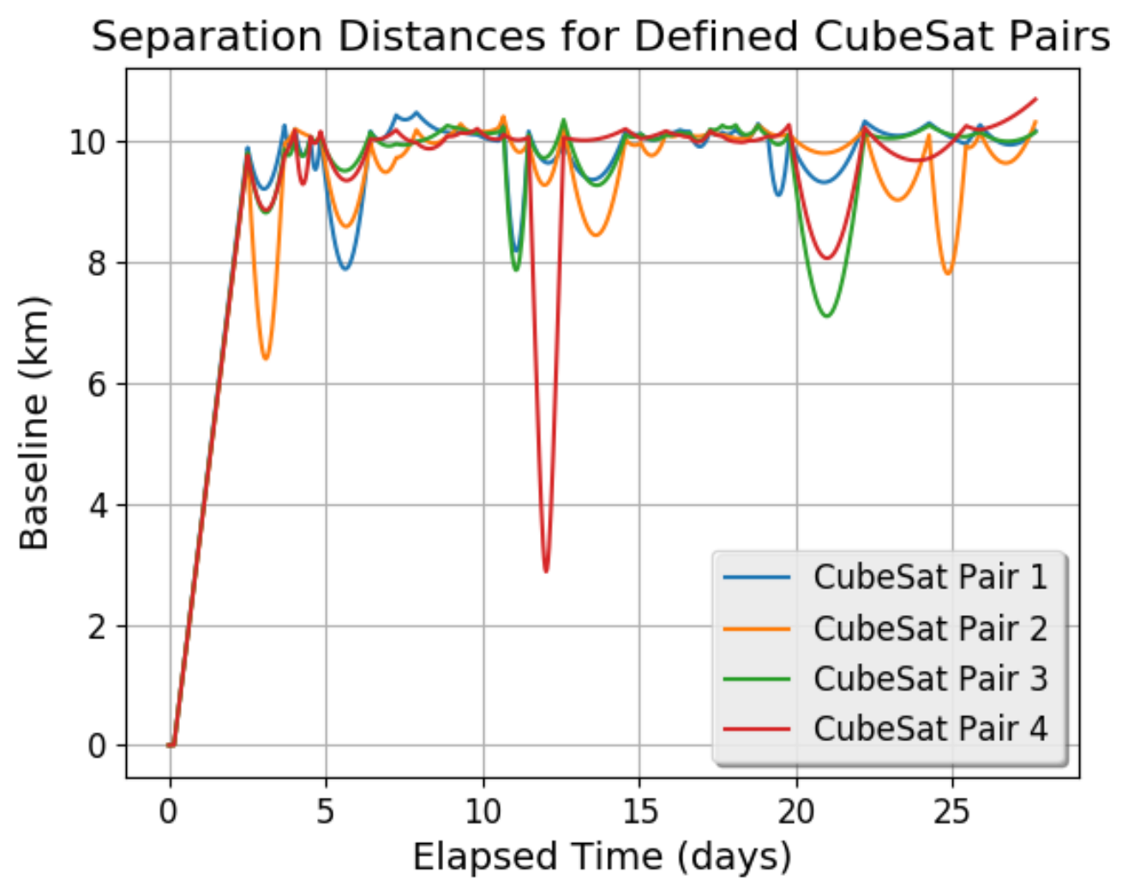


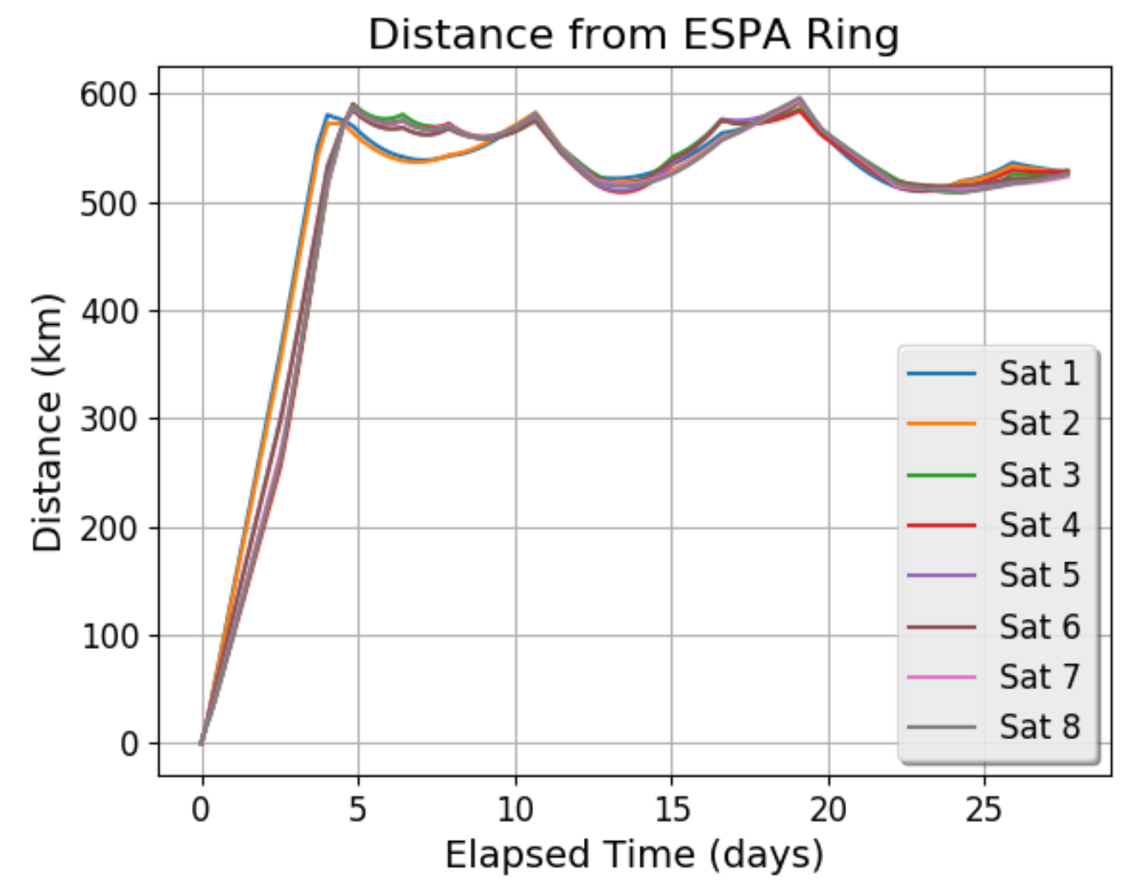
Figures 4-7. cubesat positions relative to ESPA ring. Bottom figures show trajectories in 3D; top figures show projections onto x-y and x-z planes.

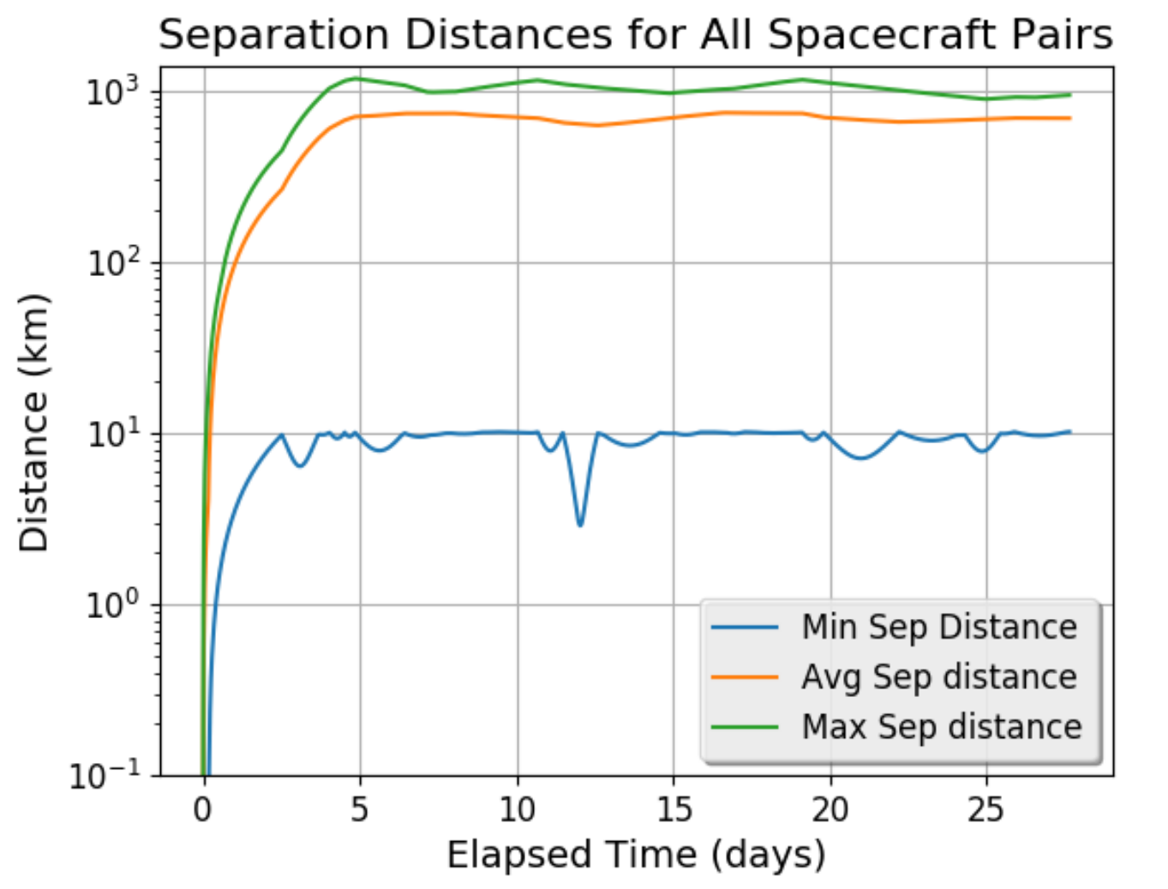
Controller Performance

- A summary of the 32 sets of maneuvers required for one month of swarm maintenance appears in Table 1. The best case required a total $\Delta\overline{v}$ of 5.21 m/s; the worst case required 9.78 m/s.
- Rather than be commanded at set times, optimal durations between maneuvers were a function of current states. The shortest window was 3.8 hours, the longest was 57.9 hours, and the average time between maneuver sequences was 19.9 hours. ***These results emphasize the requirement for onboard autonomous technology.***
- Separation distances between the defined cubesat pairs was generally 10 km, with some excursions less than 10 km during periods of free drift.
- No violation of key constraints occurred: there were no breaches in the 2 km keep-out zones, and no separations beyond 650 km from the ESPA ring deployer









	Δv Required for Each Cubesat in the Swarm							
Δv (m/s)	1	2	3	4	5	6	7	8
min:	0.0004	0.0006	0.0003	0.0007	0.0005	0.0003	0.0003	0.0011
max:	0.85	1.28	1.77	1.71	1.21	1.18	1.49	1.54
mean:	0.19	0.25	0.33	0.32	0.28	0.28	0.26	0.26
total:	5.21	6.60	9.78	9.55	8.24	8.32	7.73	7.72

Table 1. Summary of the 32 sets of maneuvers completed by the cubesat swarm. The total Δv required corresponds to approximately 250-400 grams of prop, as shown in top left plot.

Discussion and Forward Work

We have implemented a control scheme for swarm missions at the Sun-Earth libration point L1, and simulated its performance in a high-fidelity, full ephemeris model. Results indicate that this fuel-optimal approach yields maneuvers that are feasible with current COTS cubesats propulsion subsystems. Interspacecraft distances are controlled to achieve science objectives, while also meeting overall comm system constraints and avoiding collisions.

Future work is to:

- Extend the simulation duration to a 2 year mission timeline
- Perform trade studies for relative distance constraints to determine if more fuel-optimal solutions can be identified while meeting science goals.

References

[1] Roberts, C., Case, S., & Reagoso, J. (2015). "Lissajous Orbit Control for the Deep Space Climate Observatory Sun-Earth L1 Libration Point Mission," AAS/AIAA ASC 2015: AAS 15-611.

[2] MATLAB Optimization Toolbox, mathworks.com/products/optimization.html

[3] General Mission Analysis Tool, licensed under the Apache License 2.0, gmatcentral.org/display/GW/GMAT+Wiki+Home

[4] Python 3.6.2, python.org/downloads/release/python-362

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