MISSION DESIGN AND FLIGHT DYNAMICS OPERATIONS FOR THE STARLING SWARM TECHNOLOGY DEMONSTRATION

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The NASA Starling mission, launched in July 2023, represents a significant advancement in demonstrating the capabilities of small satellite swarms to operate autonomously in low Earth orbit (LEO). Starling, which consists of four 6U CubeSats, has validated critical technologies necessary for future multi-satellite missions, including autonomous formation flying and optical-based navigation. The mission successfully maintained precise formations using GPS-based orbit determination and the Starling Flight Dynamics System (FDS) to manage maneuvers and ensure operational success. This abstract provides a comprehensive overview of the Starling's flight dynamics, covering formation requirements, orbit determination, maneuver planning, and operational tools.

INTRODUCTION

The Starling mission consists of four spacecraft designed to validate key technologies for autonomous satellite swarms in LEO. These included autonomous onboard decision-making, optical-based navigation, autonomous maneuver planning and execution, and mobile ad-hoc networking.[1] These technologies were rigorously tested within the context of a CubeSat swarm that operated as a coordinated unit, maintaining precise formations and performing complex operations with minimal ground-based intervention. The mission's success marked a crucial step toward enabling robust and scalable satellite swarming capabilities, which are essential for future space exploration, Earth observation, and other space-based activities.

Starling extends the boundaries of what multi-satellite missions can achieve, balancing cost-effectiveness with capability. Previous swarm missions have devoted substantial resources to designing and operating multi-satellite formations. Missions such as the Magnetospheric Multiscale (MMS) mission and Cluster II leveraged substantial resources and capable spacecraft to design and operate swarms of four spacecraft in tetrahedral formations, enabling valuable science.[2,3] Recent formation flying missions have used small satellites to reduce the costs associated with operating multiple satellites, but a majority of these missions have used at most 2-3 small satellites.[4,5,6] Starling's use of four CubeSats flying in formation represents a step for the industry, providing a framework for design and operation of larger formations of small satellites. Starling offers opportunities

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and lessons for mission designers aiming to operate affordable, scalable small satellite formations as technology demonstrations platforms.

Four identical 6U CubeSats constitute the Starling swarm. Each Starling spacecraft includes a 2U XB1 bus built by Blue Canyon Technology (BCT), a ~2U ARC-developed propulsion system called Hamlet, and 2U devoted to payload volume.[1] Multi-satellite missions benefit from careful tracking of names and identifiers; Table 1 lists the names and identifiers of the Starling spacecraft, including internal nicknames for the four spacecraft.

Table 1. Starling Satellite Names and Identifiers

Name	Nickname	NORAD ID	International Designator
Starling-1	Blinky	57388	2023-100C
Starling-2	Pinky	57387	2023-100B
Starling-3	Inky	57389	2023-100D
Starling-4	Clyde	57386	2023-100A

This paper describes the flight dynamics design and as-flown performance for the Starling mission. The first section discusses Starling's launch and commissioning phases; this section includes discussion of a fuel leak, which disrupted the planned establishment of Starling's initial formation, and the steps Starling took to respond to this challenge. The next section describes Starling's two required formations, the in-train and Passive Safety Ellipse (PSE) formations. The final three sections discuss Starling's orbit determination, maneuver planning, and operational tools; the application of operational tools to streamline repeated orbit determination and maneuver planning tasks enabled Starling's successful and cost-effective operation of a multi-satellite swarm, providing a template for future missions to scale to larger swarms.

SPACECRAFT DEPLOYMENT AND COMMISSIONING

The deployment/separation of the Starling CubeSats was a critical phase that set the stage for the mission's operational success. The CubeSats were injected into sun-synchronous orbits (SSOs) by Rocket Lab's Electron launch vehicle as part of the "Baby Come Back" rideshare mission in July 2023. Launch took place in Launch Complex-1B in Mahia New Zealand, near the end of the two-hour launch window. Starling-1 was the first to separate from the Electron launch vehicle (LV) at 18-Jul-2023, 02:16:14 UTC (approximately 49 minutes after launch), followed in 30 seconds steps by Starling-2, Starling-3, and Starling-4 respectively. Initial separation orbits provided by Rocket Lab indicated that the CubeSats' initial average altitudes (572 to 575 km) were all within +/- 3σ of their expected values. The deployment strategy was carefully designed to minimize the relative velocities between the CubeSats and ensured that their initial orbits did not require immediate corrective maneuvers. As part of this strategy, the altitudes were such that the initial CubeSat order was Starling-4 (initial 'leader' of the swarm), followed by 3, 2 and 1 respectively during the commissioning phase. The Local Time of Ascending Node (LTAN) of the initial SSOs was approximately 01:49. All separations took place while the CubeSats were in eclipse; after exiting the Earth's penumbra, successful deployment of each CubeSat's solar arrays occurred 30 minutes post-injection in LEO. Unless performing maneuvers, the CubeSats were placed in the attitude which minimized the cross-sectional area (approximately 0.04 m^2).

However, an anomaly occurred when a leak in the propulsion system Hamlet was detected on Starling-1 shortly after deployment[7], complicating the initial drift control strategy. The propulsion leak significantly changed its initial orbit: it eventually lowered its mean altitude below the swarm average by several hundred meters, so that by early August 2023 Starling-1 became the new leader and in fact kept drifting ahead of the swarm. In addition, its eccentricity and inclination vectors eventually changed to be out-of-family with respect to the rest of the swarm.

The propulsion leak in Starling-1 necessitated a modification to the mission's original drift control maneuver strategy. Instead of executing the planned maneuvers to position the satellites into their intended in-train formation, the flight dynamics (FD) team had to devise an alternative approach that would allow the other three CubeSats to compensate for Starling-1's reduced maneuverability and large drift rate with respect to the other spacecraft. This adjustment ensured that the swarm could still achieve the desired inter-satellite distances (ISD) and begin mission operations effectively, albeit with some adjustments to the formation maintenance strategy.

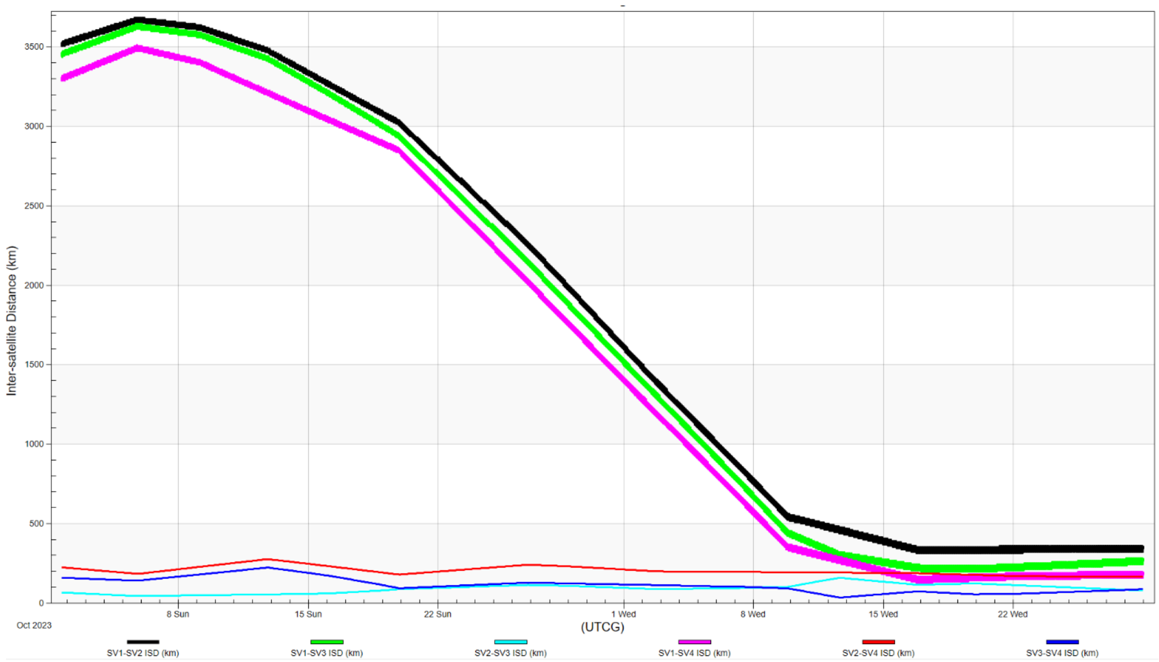

Figure 1 –ISDs between each of the Starling spacecraft from the Drift Control Maneuver (DCM) in early October 2023 through the Swarm Phasing Maneuver (SPM) in mid-November 2023.

Despite the challenges presented by the propulsion anomaly, the commissioning phase successfully positioned the CubeSats within the required parameters, allowing the mission to proceed with its planned operational phases. The experience highlighted the importance of flexibility in mission planning and the ability to adapt quickly to in-orbit anomalies.

FORMATION REQUIREMENTS

Maintaining stable and precise formation was a core requirement for the Starling mission, and it involved operating the CubeSats in two main formation configurations: the In-train formation and the PSE formation. The in-train formation involved the CubeSats flying in a linear sequence with controlled ISDs, allowing for effective crosslink communication and coordinated autonomous operations. This phase was essential for testing the swarm's ability to maintain precise alignment and spacing without extensive ground control. This formation had to be robust against minor variations caused by external forces, as maintaining a linear arrangement over time without continuous intervention would demonstrate the swarm's ability to perform highly coordinated operations autonomously. Achieving this level of coordination was key for validating that the CubeSats could manage complex tasks together, such as distributed sensing and inter-satellite communication.

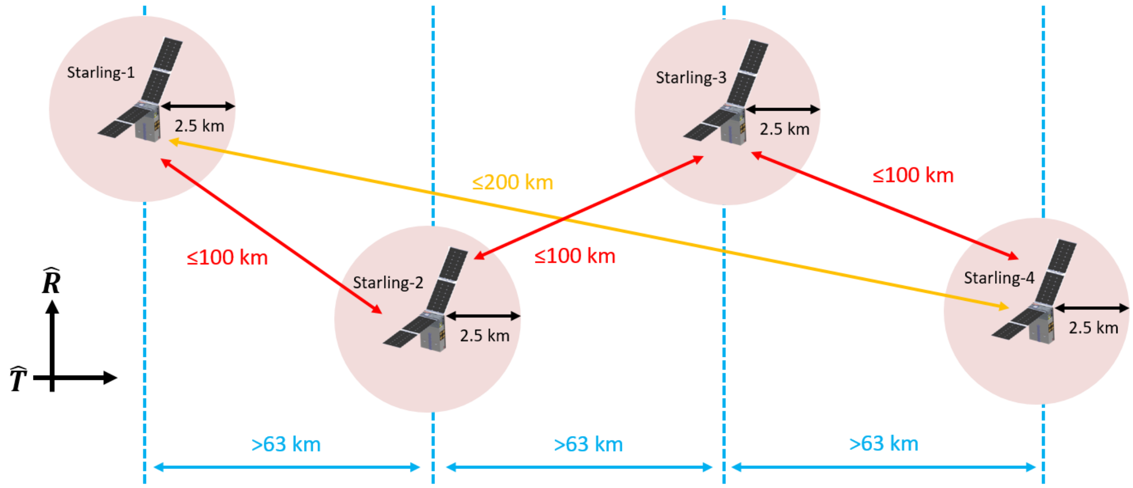

Figure 2 – Experiment and spacecraft operational requirements provide primary drivers behind Starling formation design. For the coordinate system, R represents the radial direction, and T represents the in-track direction, assuming a circular orbit

The PSE formation introduced a more complex elliptical relative motion that ensured safe separation of the satellites, minimizing the risk of collision even under off-nominal conditions.[8] This formation required control of the satellites' relative eccentricity and inclination vectors to ensure that any deviations from the desired trajectory were promptly corrected. These formations were maintained through propulsive maneuvers, designed to counteract perturbations such as differential drag, which was treated as a disturbance requiring correction rather than as a control mechanism. This configuration provided an excellent testbed for the experiments, as the swarm needed to hold its relative positions with minimal ground intervention while accounting for disturbances such as atmospheric drag and gravitational perturbations.

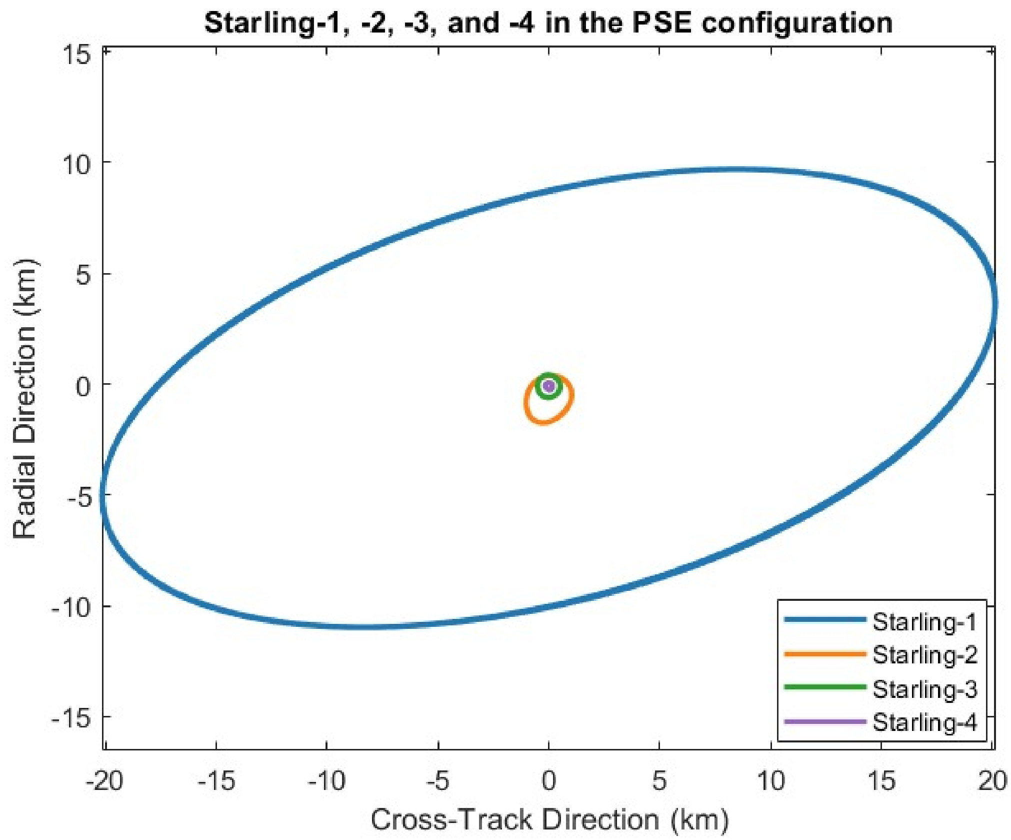

Figure 3a – Relative motion of all four Starling spacecraft in the PSE configuration, shown in the radial vs. cross-track plane. Starling-1 maintained the largest ellipse, while Starling-2, -3, and -4 followed tighter trajectories near the reference orbit.

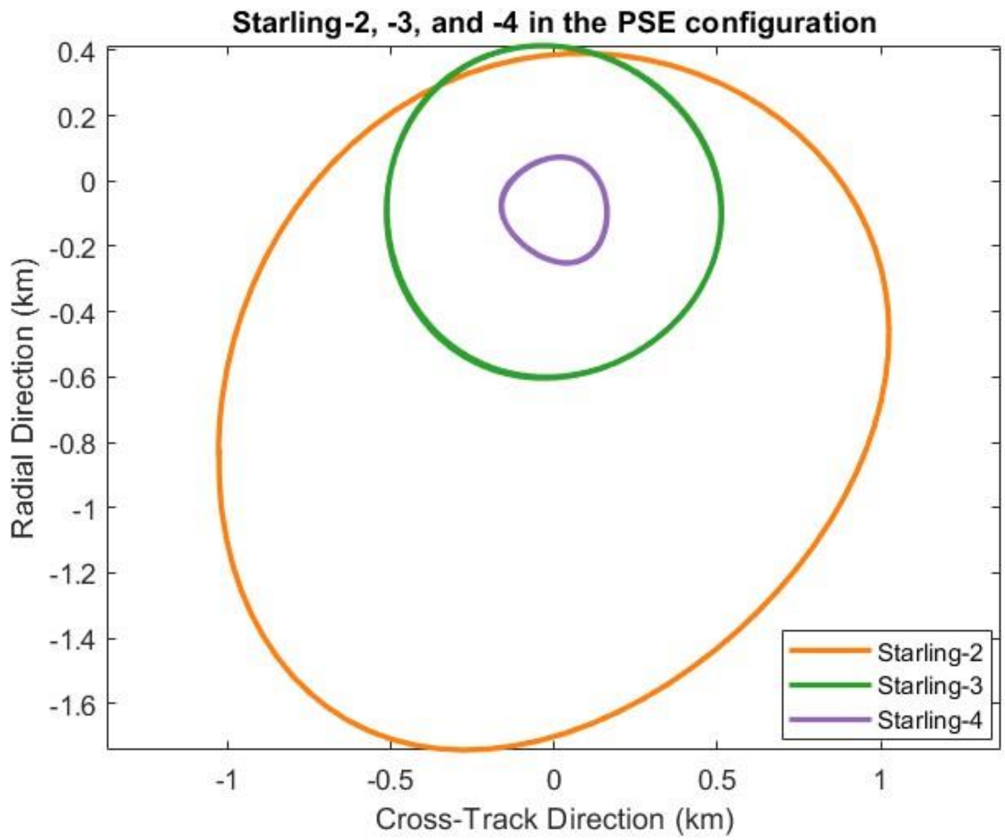

Figure 3b – Relative motion of Starling-2, -3, and -4 in the PSE configuration. Starling-3 and Starling-4 maintained elliptical trajectories near the reference orbit, while Starling-2 followed a larger ellipse to meet specific experiment objectives.

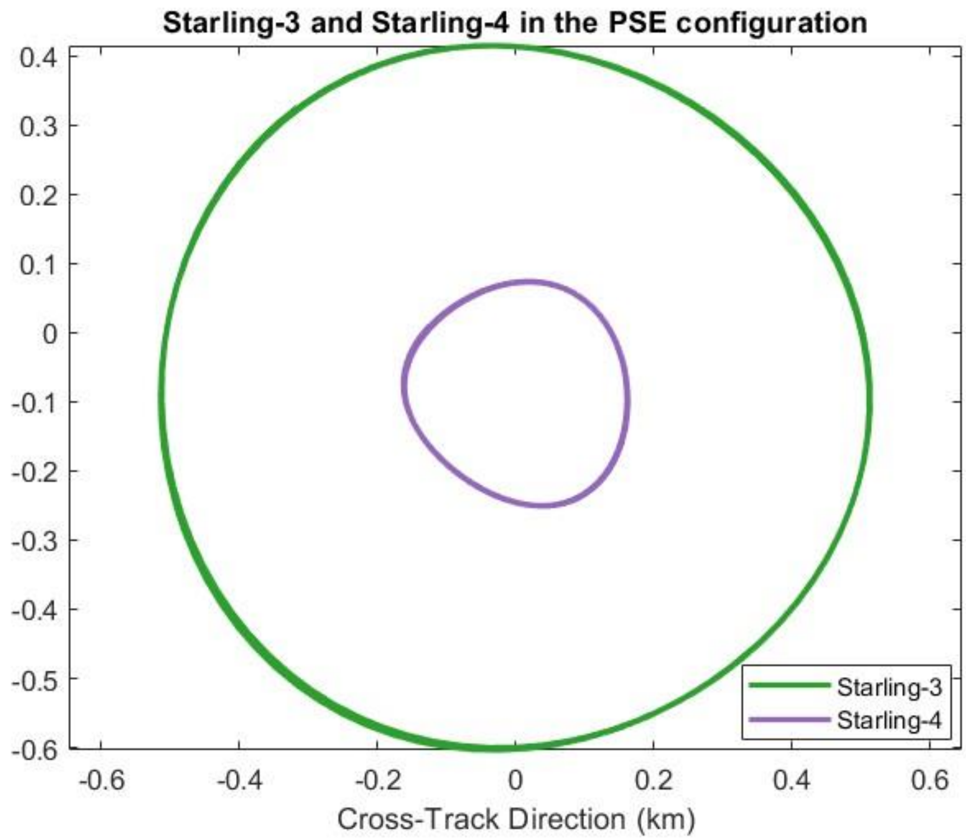

Figure 3c – Relative motion of Starling-3 and Starling-4 in the PSE configuration. The bounded ellipses demonstrate stable relative motion and controlled separation over time.

The relative motion maintained by the Starling swarm during the PSE configuration is illustrated in Figures 3a, 3b, and 3c. As shown in Figure 3a, Starling-1 occupied a large elliptical trajectory to maximize passive safety, while Starling-2, -3, and -4 highlight the bounded motion of the inner spacecraft. The experiment requirements called for Starling-3 and Starling-4 to maintain similar sized ellipses relative to the reference orbit, while requiring Starling-2 to maintain a slightly larger ellipse. These relative trajectories demonstrate the swarm's ability to sustain distinct formation geometries while satisfying both passive safety constraints and experimental objectives with weekly station-keeping maneuvers.

ORBIT DETERMINATION

Accurate orbit determination (OD) was fundamental to the success of the Starling mission. While the mission uses two KSAT-Lite ground stations* for uploading commands and downloading telemetry, the CubeSats relied solely on GPS for OD during baseline operations. Each CubeSat is equipped with a GPS receiver (NovaTel's OEM719) that provides tracking data for precise OD.

The FD team used the sequential Kalman filter and smoother within Ansys' ODTK version 6.6.1 software[9]; all four CubeSats were included in a single filter. The force model adopted uses the Earth's gravity (EGM2008 geopotential model with degree and order 21); luni-solar perturba-

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tions (with point masses); solar radiation pressure (SRP, modeled as ‘sphere with perfect absorption’), with Earth and lunar eclipses; and solid tides. For atmospheric drag, we had been using the Jacchia-Roberts model up until early February 2025; however during a semi-routine meeting with the Conjunction Assessment and Risk Analysis (CARA) group they recommended using the NRLMSISE 2000 atmospheric density model which we have been using since then. Regardless of the specific model, atmospheric drag parameters are updated daily. The propagator used is the variable-step size Runge-Kutta-Fehlberg 7(8). The specific GPS measurement-type ingested by the filter is Navigation Solution Tracking Data file (NavSol, with white noise sigma set to 3 m). The filter processes the available GPS tracking data points, expressed in Earth-Centered, Earth-Fixed (ECEF) frame, forward in time, and each CubeSat’s orbit and covariance is sequentially updated after each point is processed. After the filter is done, its output (a so-called ‘.rough’ file) is then used by a smoother (Rauch-Tung-Stribel), which processes the measurements available backwards in time (that is, it starts with the last measurement, and ends with the first measurement in the filter). Occasionally, the ‘dynamic sigma-editing’ (DSE) feature of ODTK is successfully used to deal with problematic segments of tracking data. If the filter rejects multiple measurements, DSE allows the residual-rejection threshold (nominally set to $\pm 3\sigma$) to vary based on the number of accepted measurements.

The outputs of the smoother are updated CubeSat orbit solutions in the form of ephemeris files, which are then processed by the FD team to check ISDs as well as relative orbit elements (ROEs)[8] to make sure they stay within their bounds. Corrections to parameters such as the ballistic and SRP coefficients are also computed. This approach ensured that the formation was safely maintained with the required precision, facilitating effective maneuver planning and execution; please see the Maneuver Planning section for details. Finally, each ephemeris file (and associated covariance information) is uploaded to the CARA servers for space traffic-management. The results of independent analyses by the CARA team are sent back to the Starling team a few times per day containing information about potential future conjunctions for the next seven days.

Figure 4a shows a sample plot of GPS tracking data availability for the four CubeSats during several days during May 2024. Figure 4b shows the residuals for Starling-2; the vast majority of measurements are within $\pm 3\sigma$, and therefore automatically accepted. Figure 4c shows the corresponding smoother position uncertainty evolution for the same spacecraft. It can be easily seen how the gap in GPS tracking data availability noted in Figs. 4a and 4b on May 14^{th} maps to a sudden increase in position uncertainty (especially the In-Track component which grows to a maximum of nearly 70 m), and which decreases as soon as tracking data is available again.

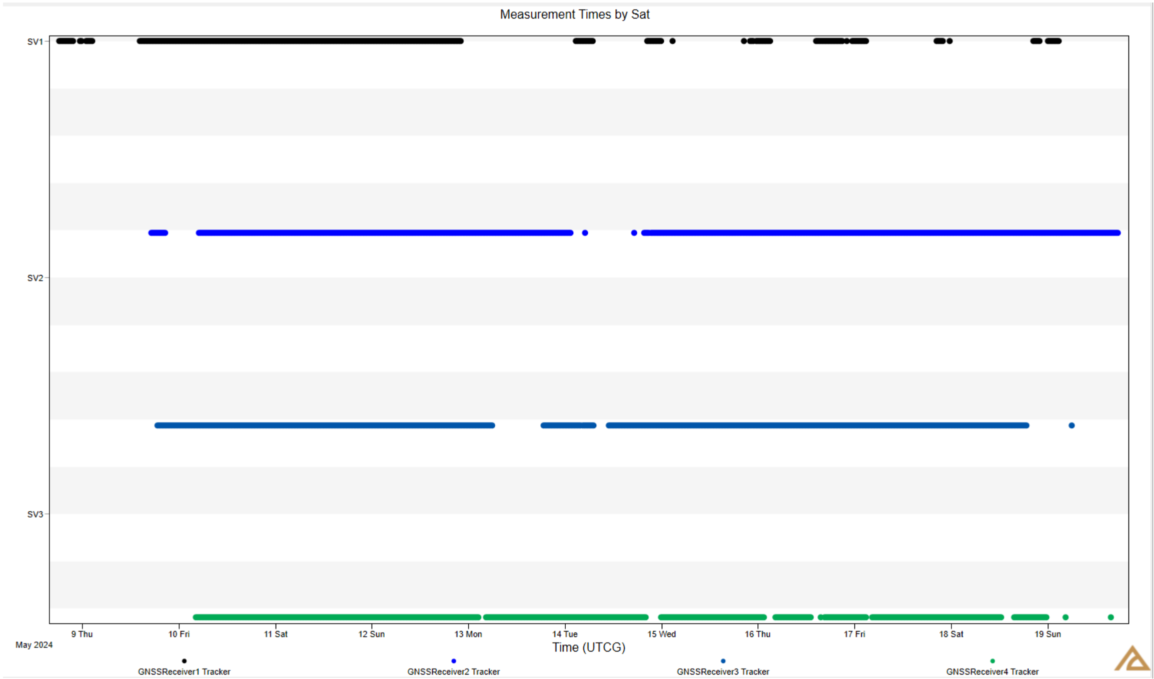

Figure 4a. Sample GPS tracking data availability during mid-May 2024 for Starling-1 (black, at top); Starling-2 (blue); Starling-3 (dark-blue); and Starling-4 (green; at the bottom).

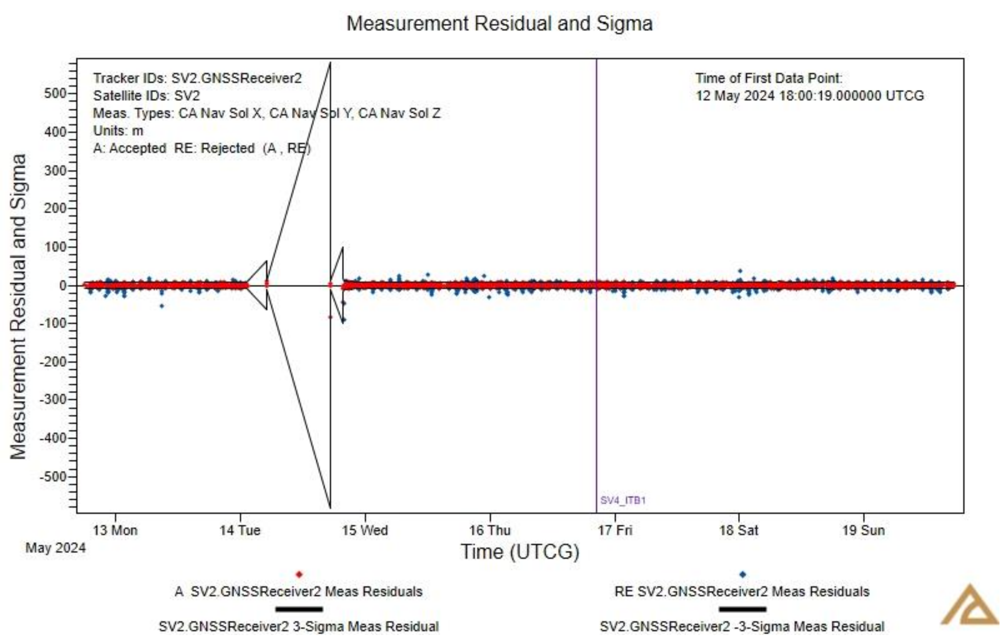

Figure 4b. Starling-2 residuals in meters corresponding to the GPS tracking data availability seen in Fig. 4a (blue line). Red points are accepted data, while blue points are rejected

data (the vertical line represents a maneuver performed by Starling-4*). Typical accepted residual 'amplitudes' are on the order of 15 m.

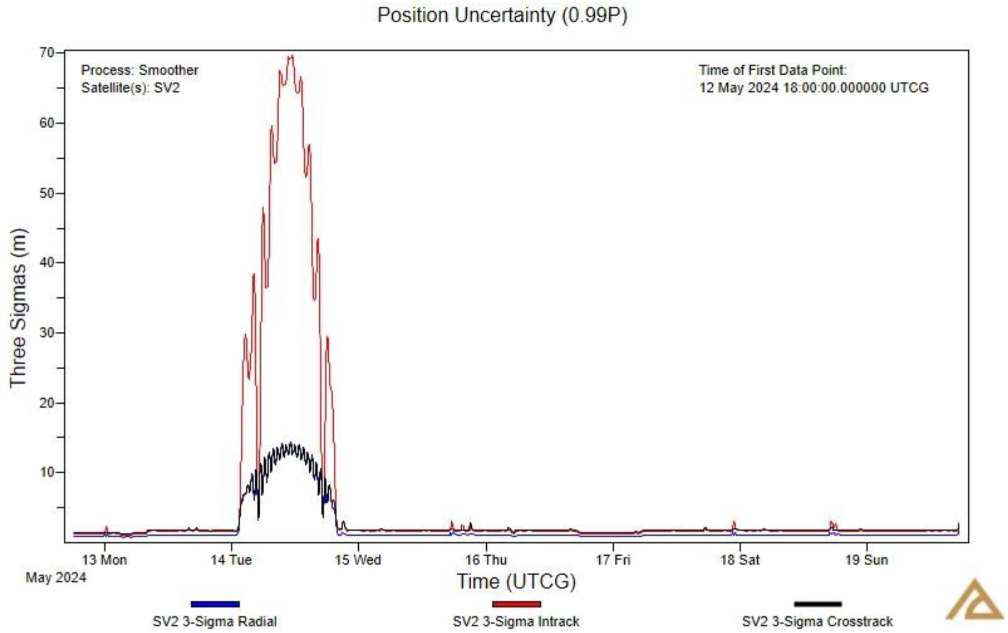

Figure 4c. Starling-2 definitive smoother position uncertainty (3σ) corresponding to Fig. 4a and Fig 4b. In-track (red) is typically the largest component. The peak in uncertainty on the 14th of May corresponds to a gap in GPS tracking data availability; see Fig. 4a.

Figure 4c shows the evolution of the smoother position uncertainty for Starling-2 during a few days in July 2024. It is noted that for that period of time we obtained a nearly continuous stream of GPS tracking data resulting in very low uncertainty components, approximately 1 or 2 meters per component (radial, in-track and cross-track). Note how radial is the smallest component. In this as well as in the previous case, plots for the evolution of velocity uncertainty (not shown) look very similar to the ones for position uncertainty. Position and velocity uncertainties for Starling-1, Starling-3 and Starling-4 are very similar to those shown in Figure 4c and Figure 5.

The GPS data-driven OD allowed the FD team to maintain the CubeSats in their intended formations with high reliability. The GPS-based system provided a robust solution for maintaining accurate orbits, which was crucial for the overall success of the mission.

* That a maneuver for Starling-4 shows up in a plot for Starling-2 residuals is a consequence of the fact that all four CubeSats are covered by a single filter-object in ODTK.

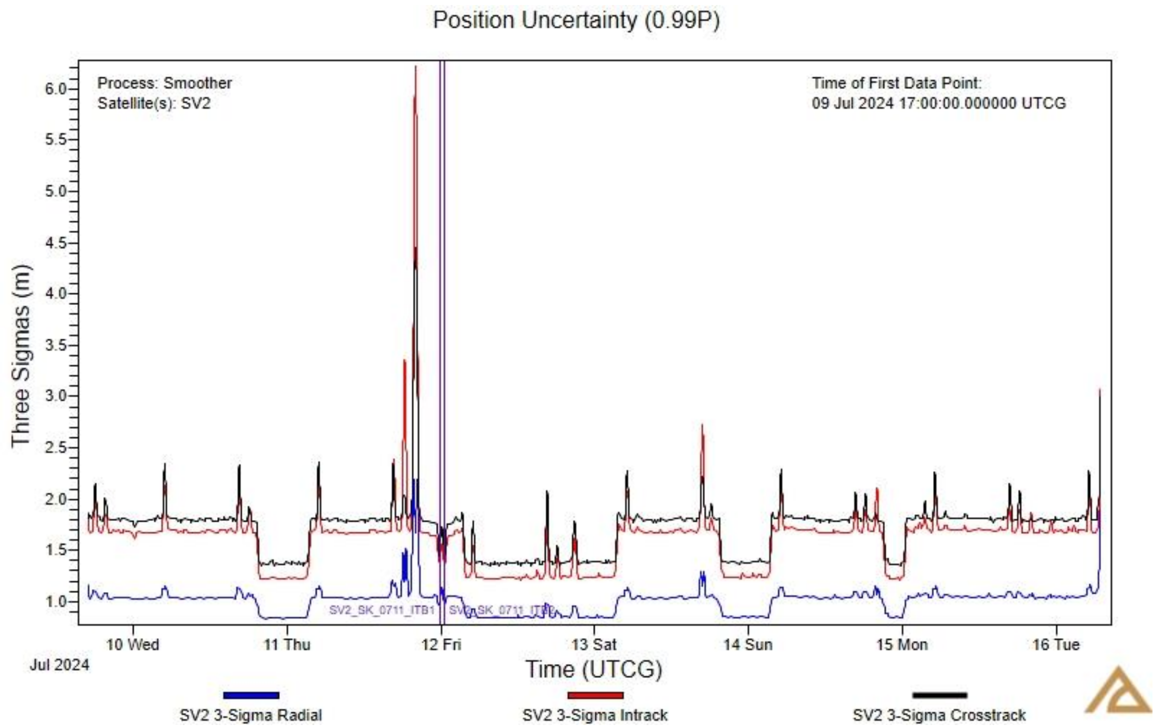

Figure 5. Starling-2 definitive smoother position uncertainty (3σ) during July 2024; the vertical lines indicate a Starling-2 maneuver.

MANEUVER PLANNING

Maneuver planning was a critical aspect of the Starling mission, executed by the FD team on the ground. The CubeSats were equipped with the Hamlet cold gas propulsion system[7], which provided the necessary delta-V for maintaining and adjusting the formation. The maneuvers were planned to achieve the desired formation configurations, correct for disturbances such as differential drag, and ensure compliance with the mission's operational constraints.

In addition to correcting for drag, the team had to compensate for the propulsion anomaly on Starling-1 by adjusting the drift control strategy and redistributing maneuvers across the remaining satellites. Each maneuver sequence was carefully timed and designed to meet ISD requirements, which minimized risk of drift and optimized formation stability without excess fuel consumption. The swarm operated with a nominal one-week cadence, with individual spacecraft maneuvering as needed within each cycle.

Table 2. Starling Maneuvers

Maneuver	Num. Burns	Cadence	Purpose
Drift Control Maneuver (DCM)	3	One-time	Establish desired drift rate to in-train slot
Swarm Phasing Maneuver (SPM)	3	One-time	Drift arrest and equalize semi-major axis (SMA)

Swarm Reconfiguration Maneuver (SRM)	3	Twice	Set eccentricity and inclination vectors to establish passive safety ellipse (PSE)
Along Track Maneuver (ATM)	2	Twice	Control along track drift to maintain desired spacing after SRM
Slot Correction Maneuver (SCM)	2	1/week	Correct in-track drift over one orbit and phase the spacecraft to its desired along-track position (during In-Train and PSE phases)
Decommissioning Safety Maneuver (DSM)	3	One-time	Establish safe configuration for disposal

The flight dynamics team employed a rigorous maneuver planning process supported by the Starling FDS. This system integrated orbit determination data and allowed the team to generate precise maneuver plans that were executed to maintain the desired formations. The maneuvers were carried out with a focus on efficiency, ensuring minimal propellant consumption while achieving the necessary adjustments to the CubeSats' orbits. The maneuver planning cadence was aligned with the mission's operational timeline, ensuring timely and accurate execution of all maneuvers.

The process also included detailed contingency planning. Each maneuver was assessed for potential impact on mission phases, allowing rapid adaptation in case of unplanned events or trajectory deviations. This proactive approach enabled the team to maintain operational objectives while effectively managing fuel resources across the mission timeline.

The process involved several critical steps, including downlinking GPS data, generating and reviewing maneuver plans, conducting CARA screenings, and coordinating with the Mission Operations Center (MOS) for final approval and execution of the maneuvers. This structured approach ensured that all maneuvers were planned and executed with the highest degree of precision, contributing to the mission's success.

The Maneuver Planning FDS Procedures utilize template STK scenarios, based on the Starling Design Reference Mission, to ultimately add planned maneuvers to the FDS database. These planned maneuvers are used by subsequent procedures to monitor the state of the cluster (generated by the Cluster Management Procedure) as well as to create a predicted state and covariance ephemeris used for mission planning, satellite acquisition, and external conjunction screening (generated by the FDS Products Generation Procedure).

OFF-NOMINAL OPERATIONS

Throughout mission operations, day-to-day activities generally followed the procedures outlined above. However, the realities of operating an active space mission required responses to dynamic off-nominal events. Single event upsets (SEU), high probability conjunctions, and intermittent propulsion performance each necessitated unique operational responses.

Approximately once per month, each spacecraft experienced an SEU that caused the bus to enter safe mode until recovered by ground operations. Any planned activities scheduled after entry into safe mode were lost if the spacecraft was not recovered in time to reload the prior command sequence. Recovery was performed by BCT, with the duration of safe mode primarily dependent on ground contact opportunities. Most SEU recoveries were completed within 24 hours; however, a few outliers required up to a week. Planned maneuvers lost due to SEUs were re-planned and executed at the next available opportunity. During safe mode, the spacecraft defaulted to a power-positive attitude with an effective drag area approximately six times higher than the nominal configuration. Extended periods in safe mode resulted in measurable intra-swarm drift, which the flight dynamics team accounted for when planning subsequent station-keeping maneuvers.

While station-keeping maneuvers nominally occurred at weekly intervals, daily conjunction screenings occasionally identified high-probability collision risks that required active mitigation via collision avoidance (COLA) maneuvers. In these cases, the CARA team provided data products to support COLA maneuver planning. These maneuvers successfully reduced conjunction risk but also introduced intra-swarm drift, which was corrected during subsequent station-keeping maneuvers. To improve response time and reduce the effect these COLA maneuvers have on the swarm configuration the space traffic management client was developed to handle these events.[10]

Finally, intermittent propulsion system issues required the use of differential drag maneuvers to manage swarm configuration. During these operations, one or more spacecraft were commanded to adopt a high-drag attitude for periods ranging from several days to multiple weeks. These attitude profiles were carefully designed to balance the need for increased drag to adjust semi-major axis with the requirement to maintain sufficient solar array power for spacecraft operations.

OPERATIONAL TOOLS

The Starling FDS played a central role in the Starling mission, providing the necessary tools for managing the complex flight dynamics operations. The Starling FDS, developed by L3Harris, supports key functions, including orbit determination, maneuver planning, and the generation of flight dynamics products such as ephemeris files, eclipse reports, and maneuver plans.

The Starling FDS consisted of two separate workstations and a remote MySQL database. It was responsible for integrating AGI's STK 11.7 and ODTK 6.0, to facilitate the automation of routine tasks such as data preprocessing, orbit determination, and product generation. These tasks were executed via C# scripts organized into procedures, listed in Table 3 below, dedicated to each step of daily operations. These procedures enabled the FD team to handle the mission's demanding operational tempo efficiently. The Starling FDS also featured capabilities for maneuver reconstruction, allowing the team to analyze the performance of executed maneuvers and make necessary adjustments to future plans.

Table 3. List of FDS procedures, their frequency of use, and their purpose

Procedure	Cadence	Purpose
Populate Database	1/Week	Used for manual data entry and general configuration of MySQL database.
Pre-Processor	Daily	Ingests tracking telemetry and converts it into required formats for later processes, retrieves latest space weather and Earth orientation parameters (EOP) data.
Orbit Determination	Daily	Executes the OD process and generates definitive satellite trajectories.

Cluster Management	Daily	Evaluates the current swarm configuration and starting point for maneuver planning.
Maneuver Planning	1/Week	
Maneuver Assessment	1/Week	Generates maneuver acceleration history files that are used in conjunction with the orbit determination process to evaluate maneuver performance
Products Generation	Daily	Produces predicted orbit trajectory for CARA conjunction analysis, as well as assorted reports utilized by the project for daily operations.

Daily operations start with the preprocessor procedure, where new space weather, earth orientation parameters, and tracking data are gathered and transformed into the necessary formats for use in later procedures. The orbit determination procedure is then run to process this tracking data into a definitive ephemeris for each spacecraft in the swarm. These results are then used as the initial state for the cluster management procedure and the products generation procedure. The cluster management procedure is used daily to evaluate the current state of the swarm and evaluate the effects of any proposed or planned maneuvers. Finally, the products generation procedure is used to produce all the reports as required by the project.

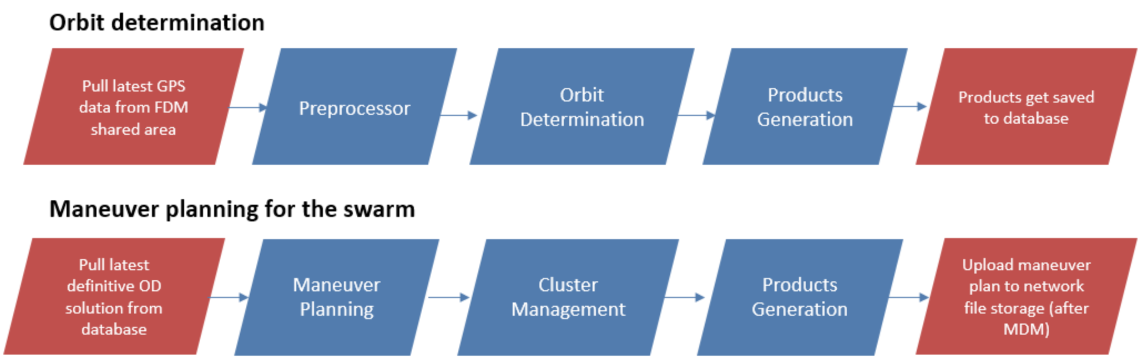

Figure 6 – Orbit determination and maneuver planning workflows supported by the Starling FDS.

The Starling FDS was designed to provide a flexible and robust framework for managing the mission's flight dynamics, ensuring that the CubeSats operated cohesively as a swarm. Its advanced capabilities allowed the flight dynamics team to maintain the necessary precision and reliability in orbit determination and maneuver planning, which were critical for the mission's overall success.

CONCLUSION

The NASA Starling mission's success marks a significant milestone in the advancement of multi-satellite spaceflight. Starling's mission architecture and technology demonstrations provide an example of how to affordably scale multi-satellite swarms. The operations team recovered the formation after a propulsion system leak disrupted Starling's early operations, exemplifying both the risks associated with lower cost spacecraft and the flexibility available to reconfigurable swarms. Starling's In-Train formation demonstrated the capability of SmallSats to maintain precisely coordinated flight, and its PSE formation exemplified a risk-reduction strategy for swarm missions.

Starling's flight dynamics architecture has proven resilient to challenges characteristic of budget-constrained SmallSat missions. Orbit Determination using GPS measurements provided the reliable trajectory solutions necessary to maintain precise relative motion, robustly recovering from measurement gaps. Starling's maneuver planning scheme successfully adapted to the propulsion anomaly on Starling-1, rebalancing maneuvers across the other three spacecraft and avoiding unnecessary fuel expenditure. The mission's flight dynamics operators have learned to respond to substantial orbit deviations caused by attitude changes during recurring safe mode entries. A Flight Dynamics System to streamline workflows proved essential for affordable swarm operations, allowing a small team of flight dynamics operators to maintain situational awareness, adapt to changes in spacecraft conditions, and fulfill obligations to CARA.

Now in its extended mission phase, Starling continues to build a foundation for future missions requiring coordinated multi-spacecraft operations. Starling's extended mission experiments augment its contributions to multi-satellite spaceflight, pushing boundaries in space traffic management and swarm control using differential drag. The mission's flight dynamics, supported by the robust and versatile Starling FDS, provides valuable insights into the challenges and opportunities of satellite swarms, laying the groundwork for a new chapter of larger and more capable swarm missions.

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