AAS 24-365

HELIO SWARM

THE NATURE OF TURBULENCE IN SPACE PLASMAS

Flight Path Control Error Analysis for the HelioSwarm Observatory

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Introduction & Outline

Goal
Evaluate the impacts of maneuver execution errors and maneuver planning timeline constraints on the science performance of the HelioSwarm Observatory.

- HelioSwarm mission overview & concept of operations
- Node trajectory design and maneuver strategy
- Node orbit determination & maneuver estimation
- Node flight path control
- Implications for missions using “swarm” architecture

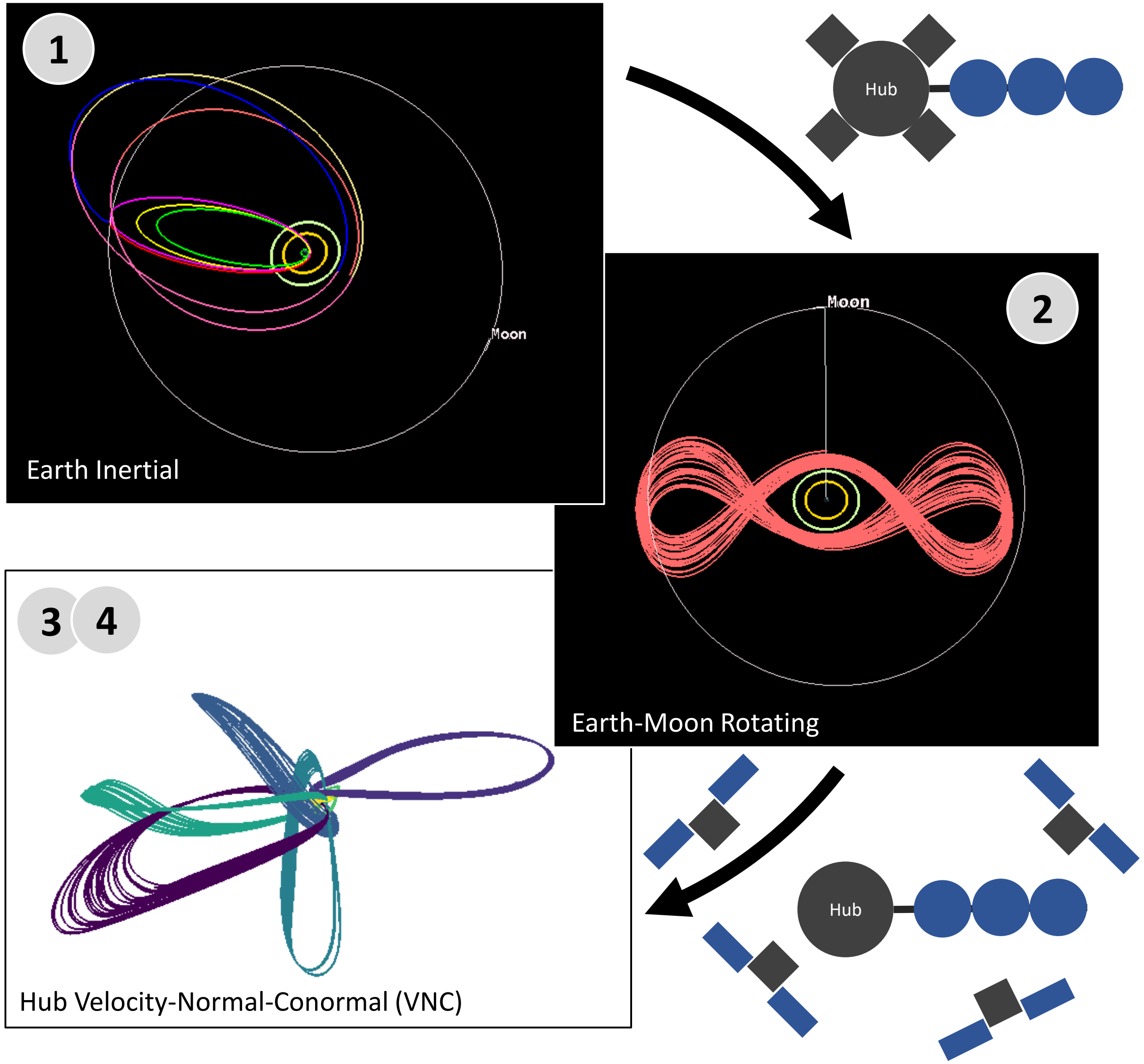
HelioSwarm Overview

HelioSwarm is a NASA Medium-Class Explorers (MIDEX) mission to study solar wind turbulence using a swarm of nine satellites in a highly eccentric, 2:1 lunar resonant orbit (“P/2”)

- “Hub” spacecraft is based on a propulsive ESPA
- Hub transports “Nodes” to science orbit and provides communications, timing, and ranging for the Observatory
- Node spacecraft is based on a commercial small satellite bus with identical instrument suites including a faraday cup, fluxgate magnetometer, and scan coil magnetometer
- Hub carries an identical instrument suite to the Nodes with the addition of an ion electrostatic analyzer to provide context to the Node measurements

Concept of operations:

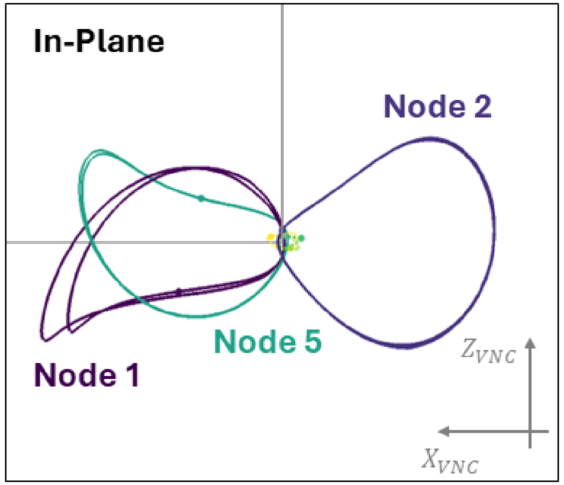
1. Hub launches to first of 3.5 phasing loops to a lunar gravity assist
2. Hub maneuvers to 2:1 lunar resonant HEO
3. Once established in science orbit, Nodes separate from Hub and independently maneuver to nearly-repeating relative trajectories (“loops”)
4. Nodes perform periodic maneuvers to maintain relative trajectories



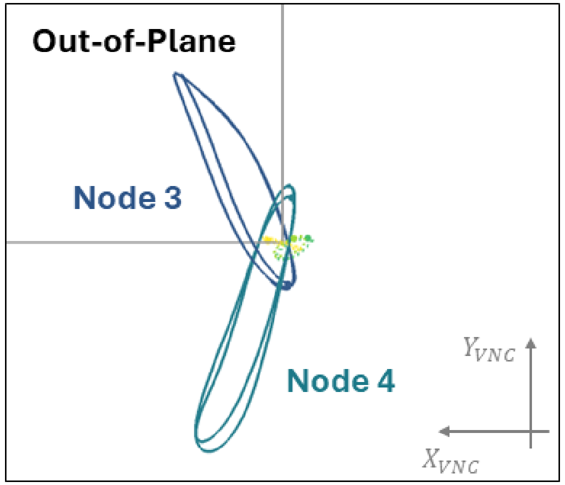
Swarm Architecture

Eight free-flying Nodes nominally occupy nearly repeating trajectory “loops” about the Hub spacecraft

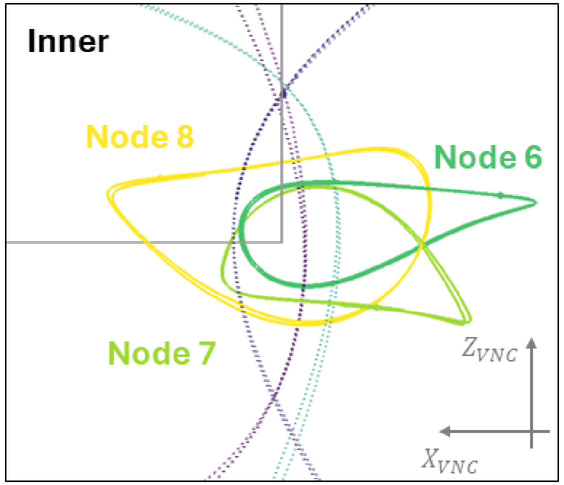
- For this work, categorize as **in-plane**, **out-of-plane**, and **inner** loops
- Categories assigned for convenience and dynamical similarity, not science or swarm function



In-Plane loops have large amplitudes (10^3 km) with motion predominately in the Hub orbit plane



Out-of-plane loops have large amplitudes (10^3 km) with motion predominately along the Hub orbit normal (some along-track components)



Inner loops around the Hub, remaining within ~250 km at all times, primarily contribute to small-scale observations

Swarm design causes Observatory to naturally evolve into geometries that satisfy two configuration requirements:

- **Polyhedral**

Requires two individual polyhedra (design focuses on n=4 polyhedra) where the root sum square of elongation and planarity ($\sqrt{E^2 + P^2}$) is <0.6 with a 3:1 difference in size

- **3D**

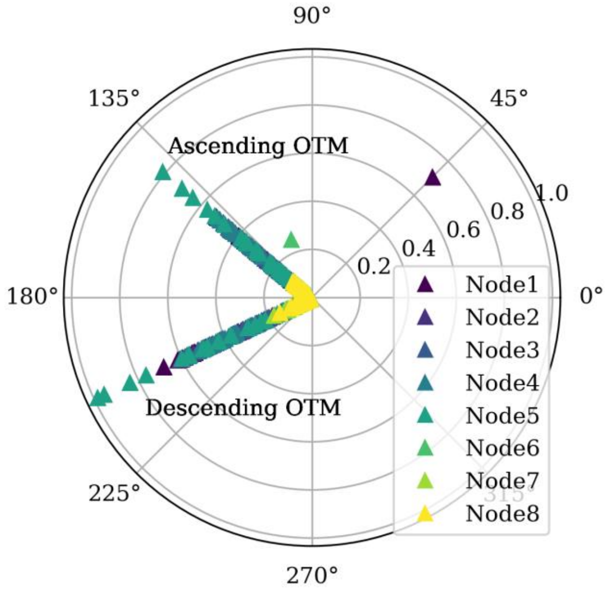
Requires short (25-100 km), medium (100-1200 km), and long (>1200 km) components of inter-satellite displacements both along and across the Hub-Sun line

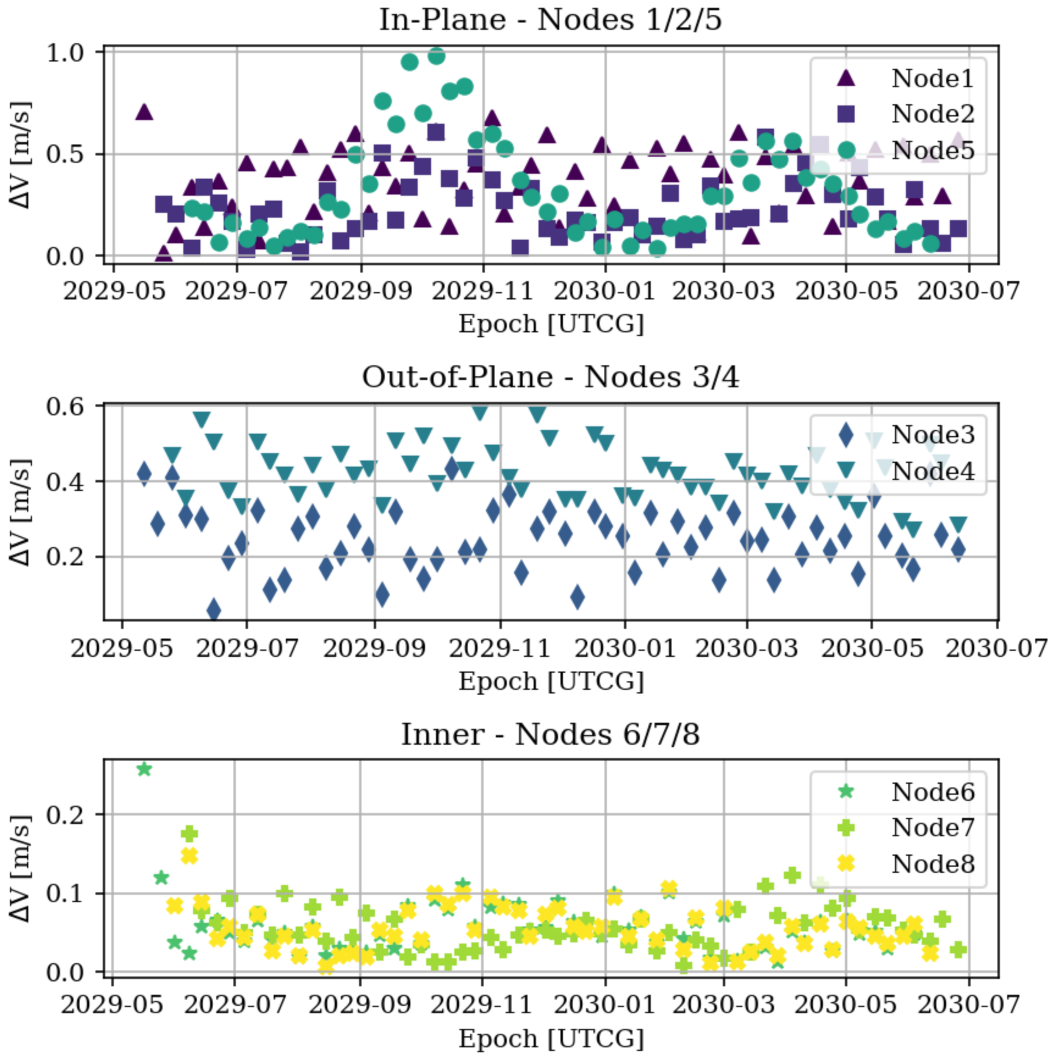
Configuration requirements can be satisfied simultaneously or independently

Node Maneuvers

Nodes nominally perform **two** orbit trim maneuvers (OTMs) every revolution to maintain the relative trajectory

- ➢ Ascending OTM located at 140° true anomaly
- ➢ Descending OTM located at 205° true anomaly
- ➢ In current design reference mission (DRM), first ascending OTM placed at insertion maneuver true anomaly





Node OTM magnitudes vary with amplitude of relative motion

- ➢ In the DRM scenario, all OTMs serve deterministic purpose to target back to the desired loop
- ➢ In operations, OTMs will include a statistical component (not modeled here) to correct for previous dispersions/errors
- ➢ All OTMs included in DRM, including those with magnitudes below the threshold where a maneuver would be waived (future analysis)

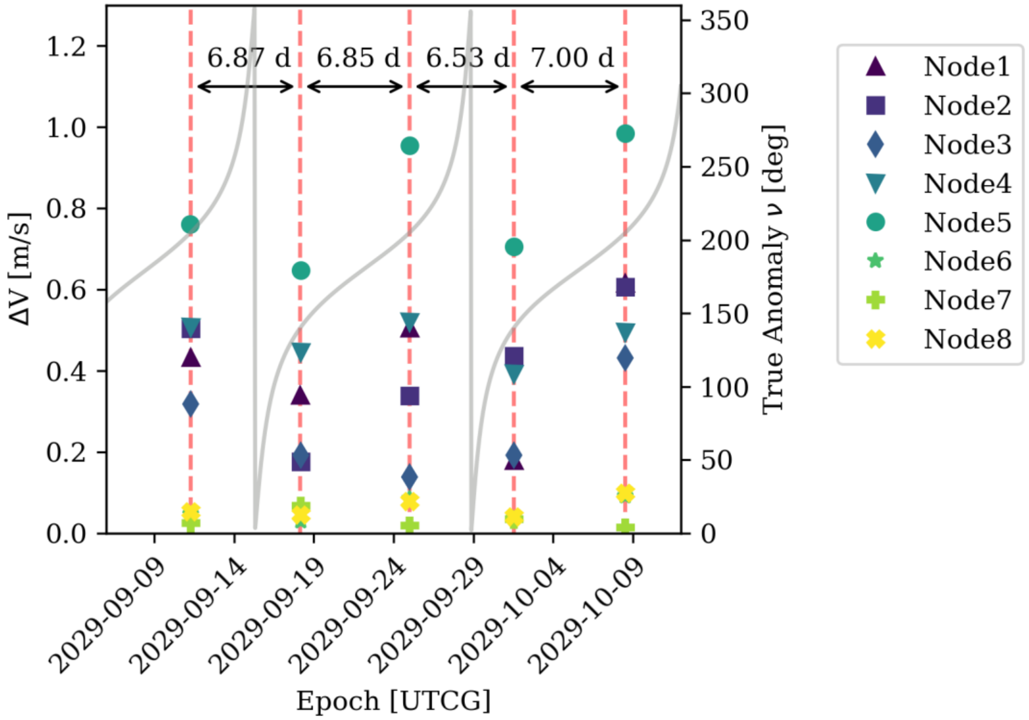
Node Operations Cycle

Node OTM cadence varies with period of science orbit, between 6-7 days for majority of the science phase

- Typical post-maneuver operations cycle requires performing orbit determination, estimating the actual value of the maneuver as performed, and planning the next OTM from this post-maneuver state
- Spacecraft motion is slow in highly eccentric lunar resonant orbit (IBEX operational experience) with a significant portion of a revolution required to collect sufficient measurements to estimate the preceding maneuver

Node maneuver cadence is twice per revolution

- 6-7 day period between each maneuver may be insufficient for typical operations cycle
- OTM may have to be planned without complete knowledge of prior OTM performance



The post-burn time required to estimate each maneuver may preclude statistical estimation of the prior OTM when planning the upcoming OTM, degrading the accuracy of Node flight path control

Node Orbit Determination

Use previous Node OD error analysis setup to evaluate time required to estimate small maneuvers in 2:1 lunar resonant orbit

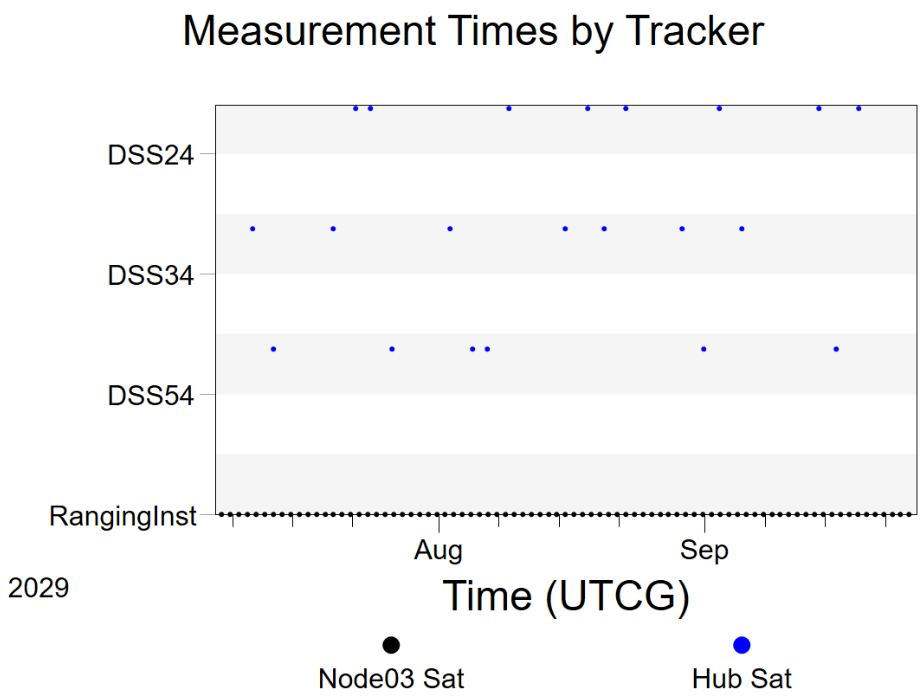
- Ansys' Orbit Determination Tool Kit (ODTK) scenario to simulate measurements and process them through a filter/smoother pair to estimate maneuver magnitude/direction

Both Hub and Node measurements required to estimate Node absolute states

- Hub tracked by NASA Deep Space Network, DSN sequential range and total count phase (TCP) measurements
- Node tracked by Hub ranging transponder ("RangingInst"), space-based range (SB Range) measurements

Notional tracking schedule used for analysis

- Hub tracked 4x/revolution at true anomalies [90°, 150°, 210°, 270°]
- Node tracked daily for a 30 minute period generating measurements every 5 sec



Node Maneuver Estimation

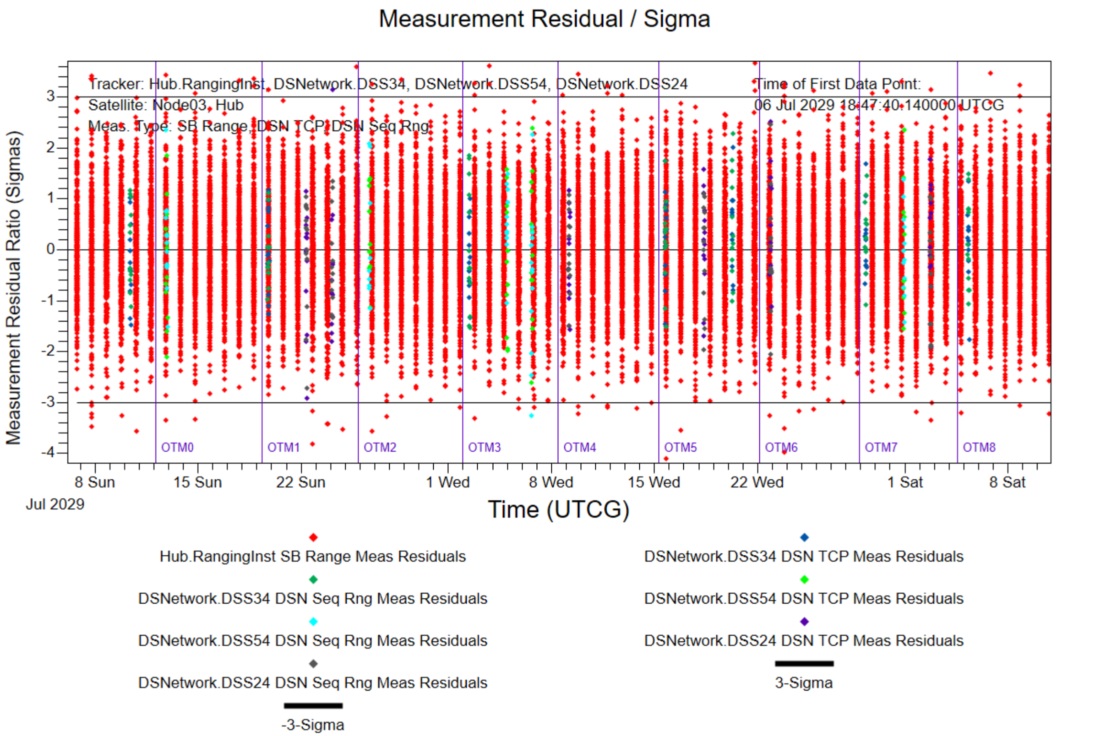
Node maneuver estimation study seeks to quantify how quickly the filter/smoother combination converges after a maneuver

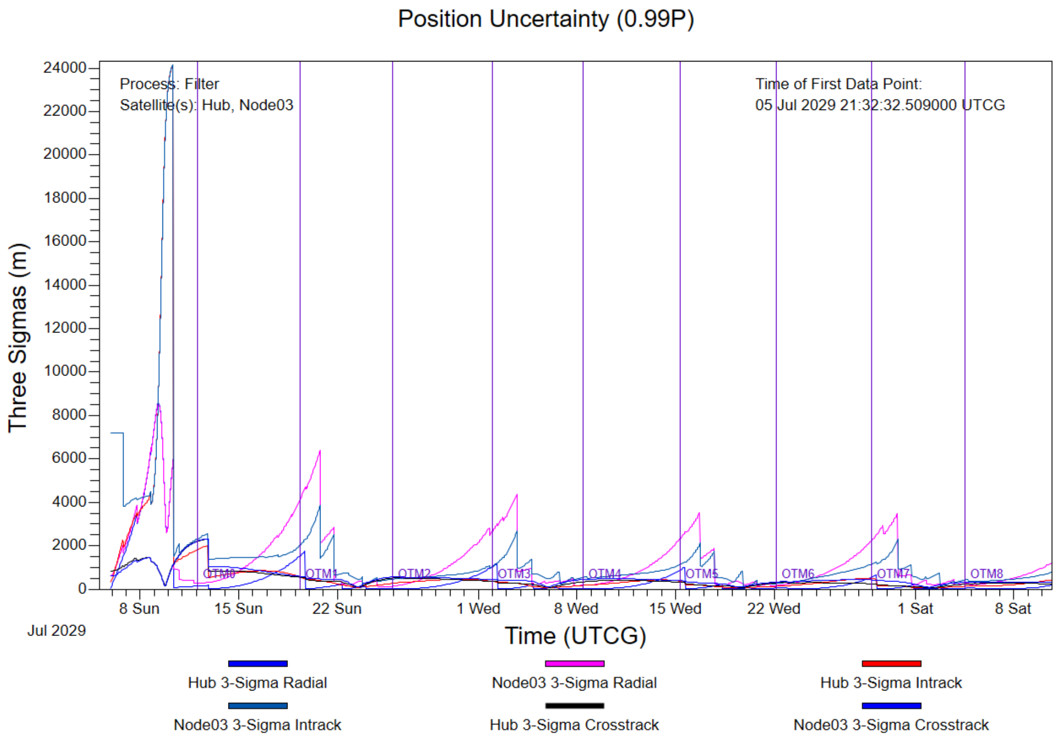
- Simulate tracking data for 5 revolutions, generating both Hub and Node measurements
- To represent an initialized filter with tracking system calibrated, run several revolutions giving the filter truth values for each maneuver
- To represent unknown execution errors on the final maneuver in the filter span, perturb the values given to the filter (truth values remain constant)
- To isolate maneuver convergence, model a scenario where **no further OTMs** are performed after the final, perturbed maneuver

Step through one revolution of ranging sessions after an OTM to observe convergence behavior of estimated OTM error (estimated – actual)

- Separately examine ascending and descending maneuvers due to different post-maneuver dynamics

Maneuver Estimation Study





Filter residual ratios (measurement residual divided by measurement root error variance) show filter accepting measurements for both Hub and Node across all maneuvers prior to final perturbed maneuver

- Filter initialized with truth values for OTMs

Position uncertainty shows large initial transient (artifact of filter initialization in ODTK analysis setup) followed by steady state fluctuations in Node uncertainty, correlated with orbit period

Maneuver Estimation Timeline

Ran maneuver estimation analysis on Nodes 1-4

- Inner nodes have small maneuvers that are difficult to estimate with a standardized configuration (required for the comparison)

Applied same 5%, 5° perturbation to final maneuver

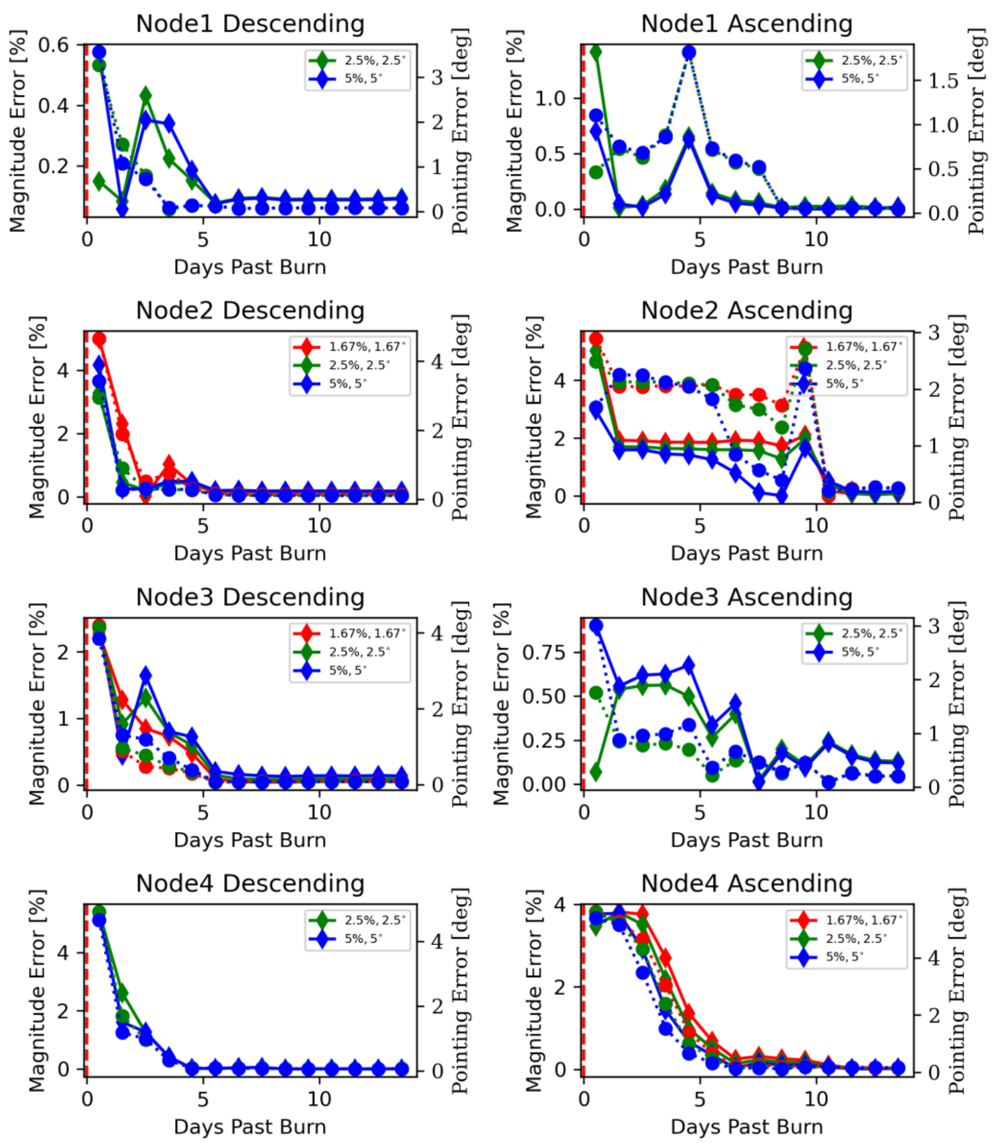
- Filter configured to represent this perturbation being a 3, 2, or 1σ error (by changing the uncertainty specified on the planned maneuver parameters)

Descending maneuvers generally reach steady state ~5-6 days after the burn

Ascending maneuvers require longer and exhibit less definitive convergence behavior

Attribute difference between ascending and descending maneuvers to slower apparent motion during apogee arc (after ascending maneuver) compared to perigee arc (after descending maneuver)

Due to the 6-7 day maneuver cadence, all Node OTMs cannot reliably be recovered prior to planning the next OTM



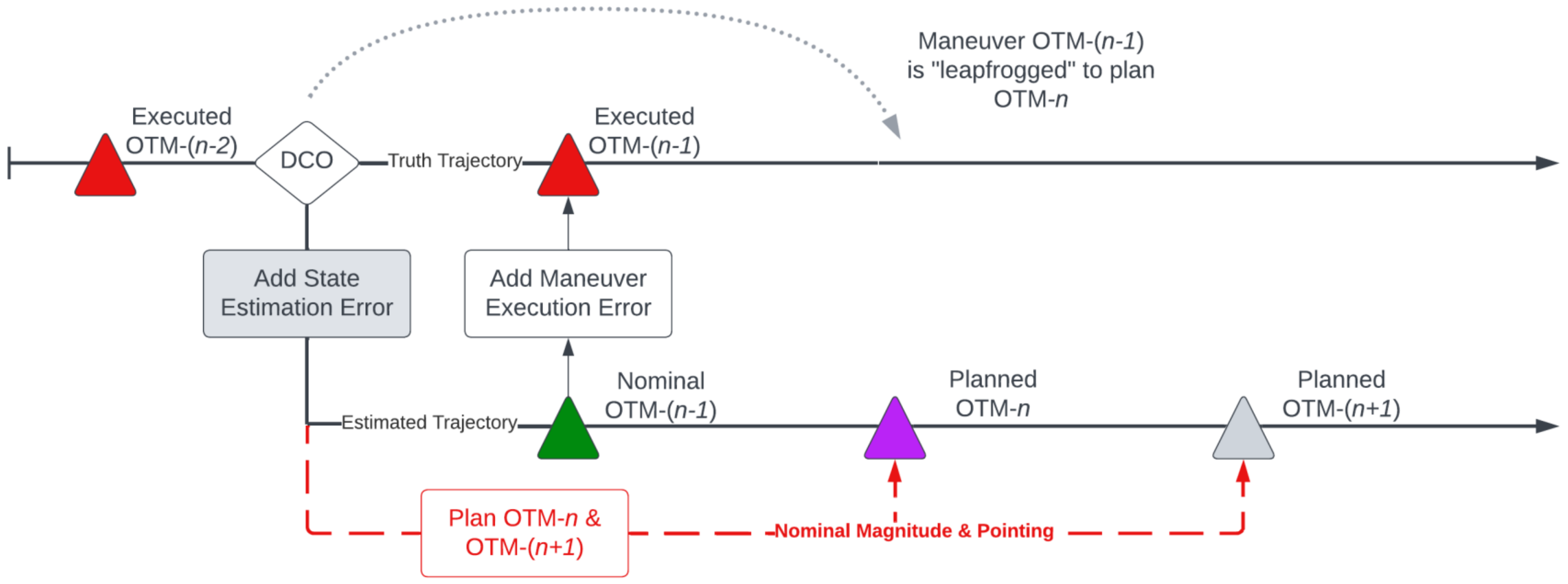
Flight Path Control Analysis

Flight path control is defined as the capability of the Node spacecraft to accurately maintain its assigned relative trajectory

- ➢ Maneuver planning timeline constraint precludes incorporating knowledge of previous OTM performance when planning next OTM
- ➢ Targeting algorithm for trajectory design requires two impulses, include next OTM in planning cycle

This approach "leapfrogs" the previous OTM (n-1) when planning each OTM

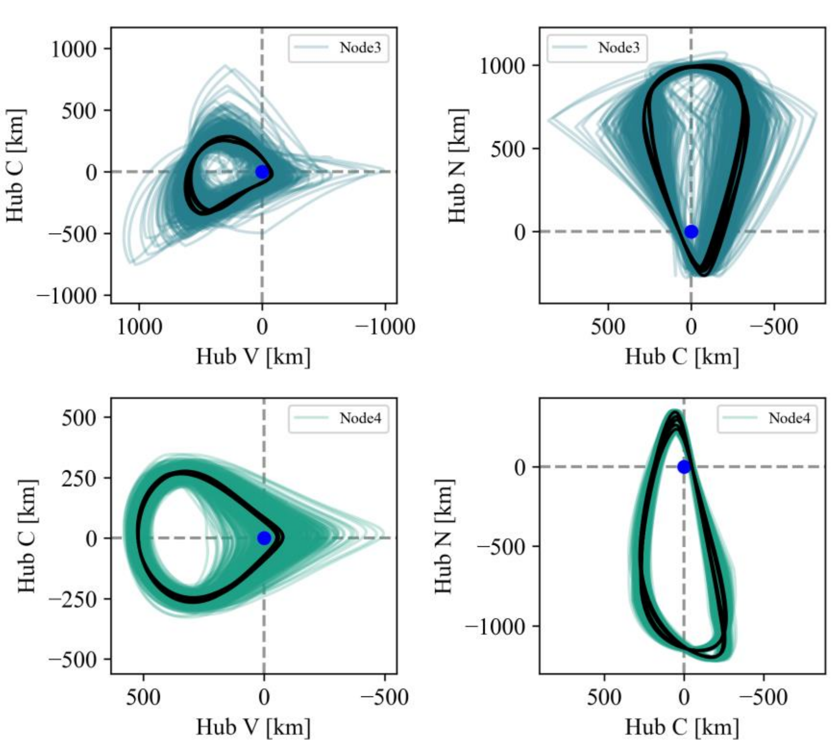
- ➢ The loss of performance information will contribute to flight path control error



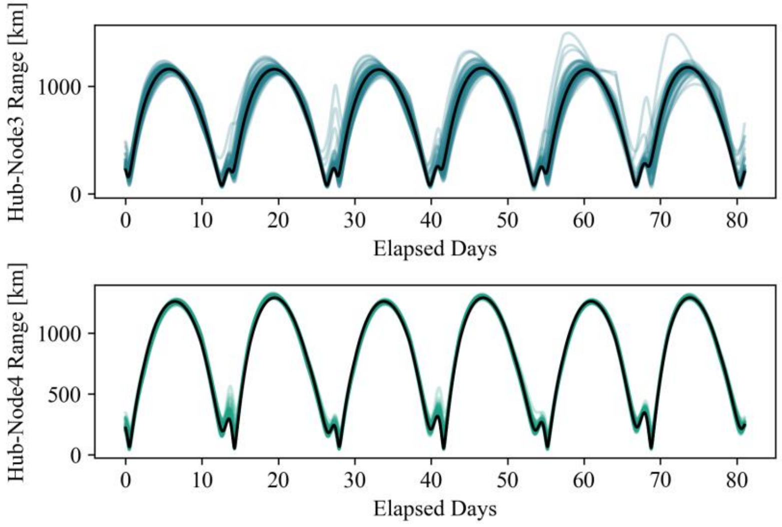
Analytical setup uses a Monte-Carlo method to apply randomly sampled maneuver execution error and study the propagation of flight path control error with maneuver planning timeline constraints

- ➢ No additional state estimation error is applied, isolating the maneuver planning constraints as the primary source of a-priori error
- ➢ All maneuvers modeled impulsively allowing simple magnitude and direction errors to be sampled/applied

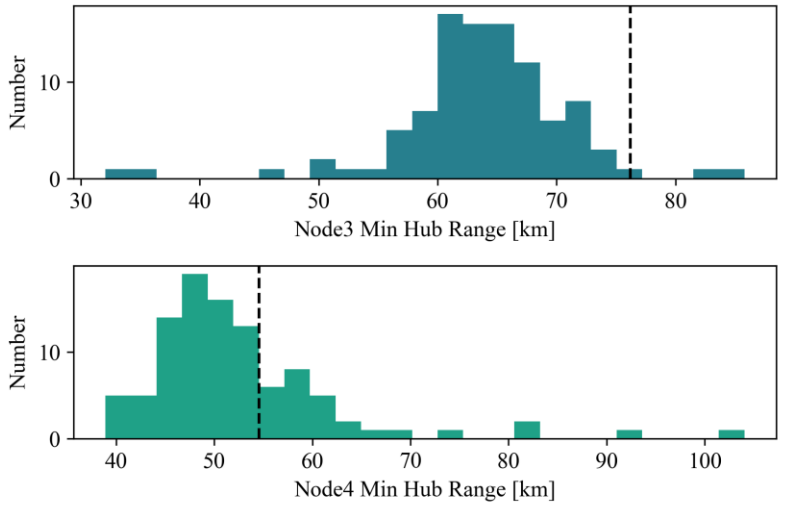
Results – Out-of-Plane Nodes



100 dispersed Node trajectories shown in Hub-centered VNC (velocity-normal-conormal) reference frame



Hub-Node range for 100 dispersed Node trajectories

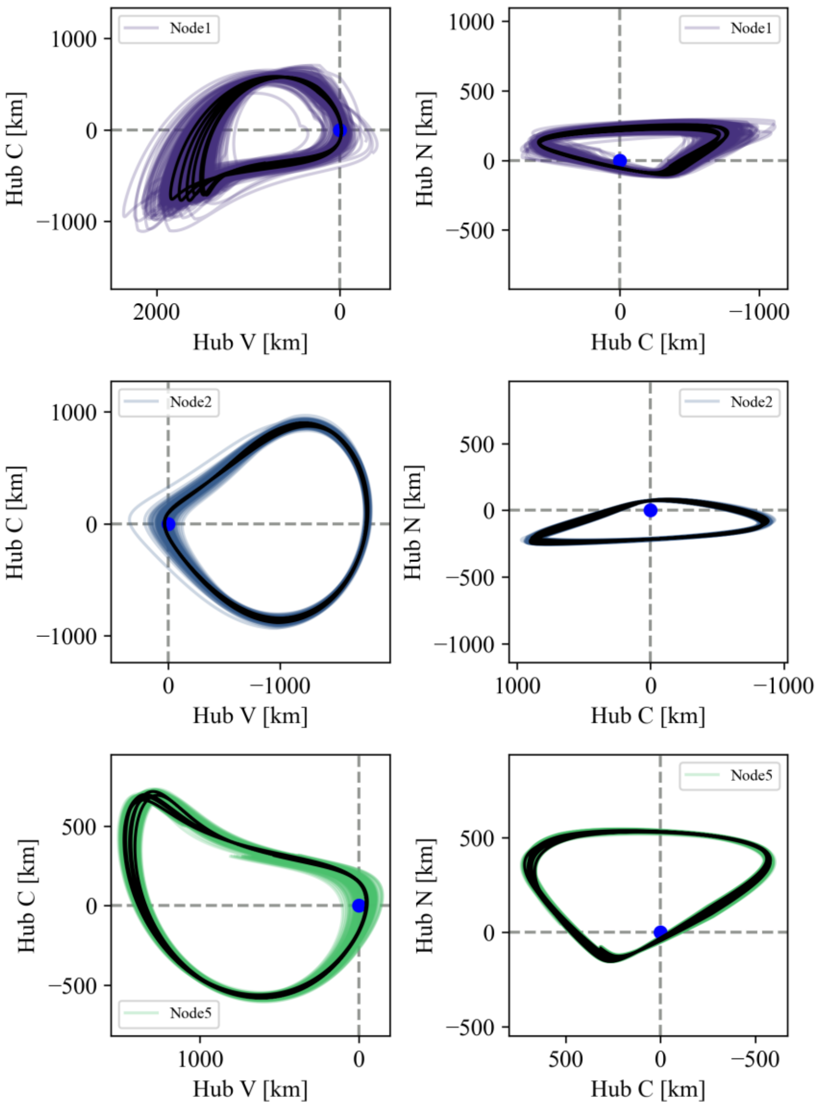


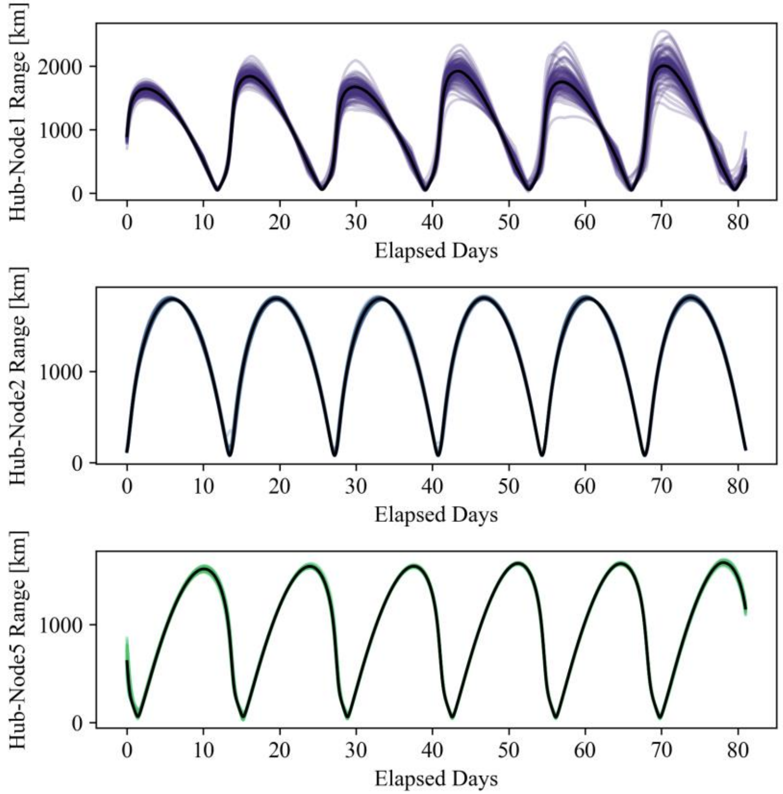
Minimum Hub-Node range for 100 dispersed Node trajectories

Performed flight path control error analysis for out-of-plane, in-plane, and inner Nodes

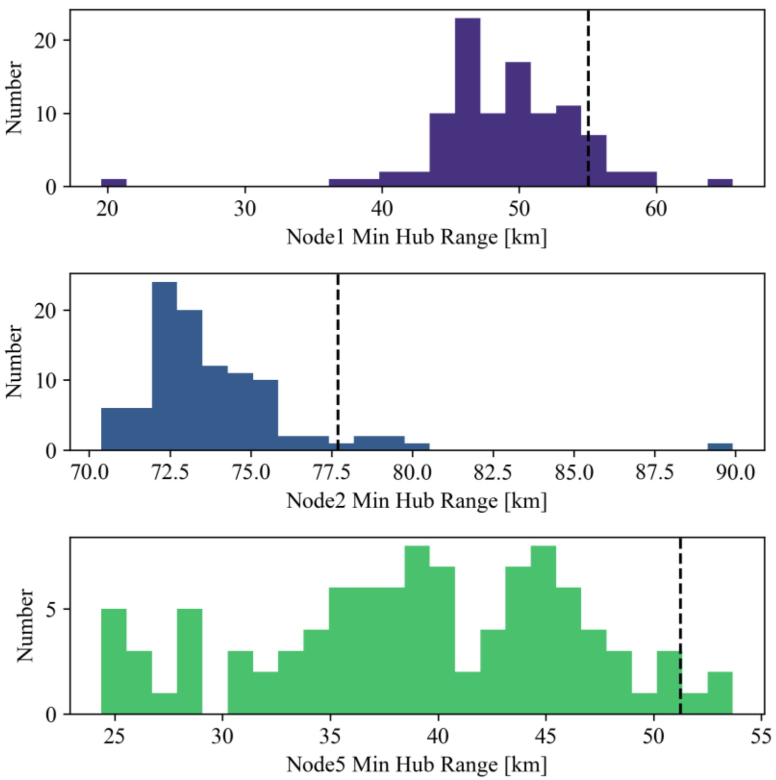
- 100 iterations of ~6 revolutions in science orbit
- Applied 5%, 5° maneuver execution error to all maneuvers
- "Leapfrog" maneuver planning constraint applied with no state estimation error

Results – In-Plane Nodes





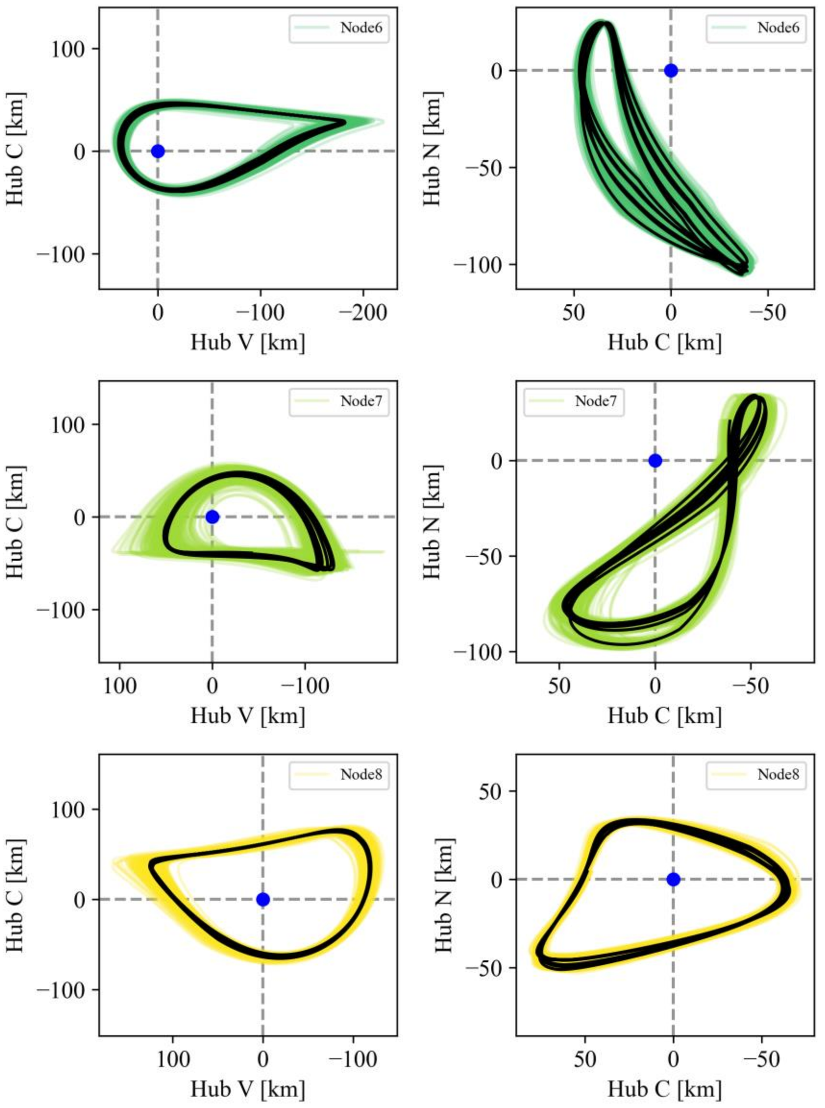
Hub-Node range for 100 dispersed Node trajectories

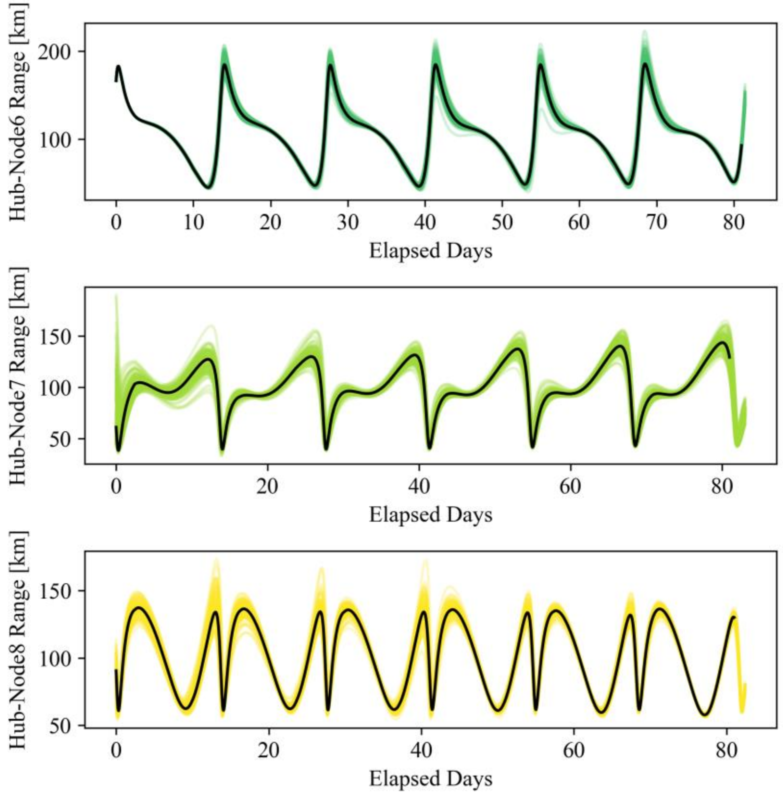


Minimum Hub-Node range for 100 dispersed Node trajectories

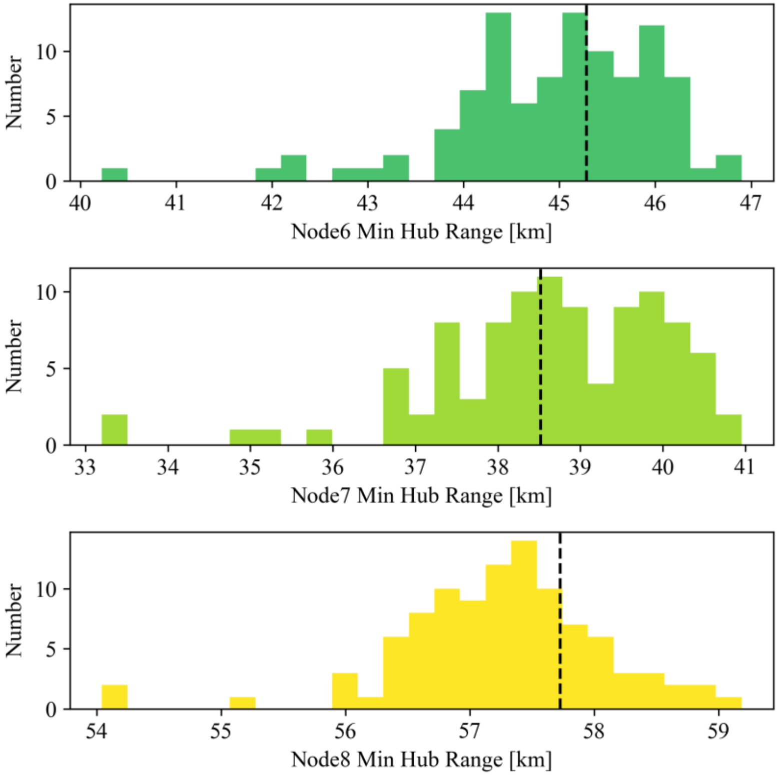
(left) 100 dispersed Node trajectories shown in Hub-centered VNC (velocity-normal-conormal) reference frame

Results – Inner Nodes





Hub-Node range for 100 dispersed Node trajectories



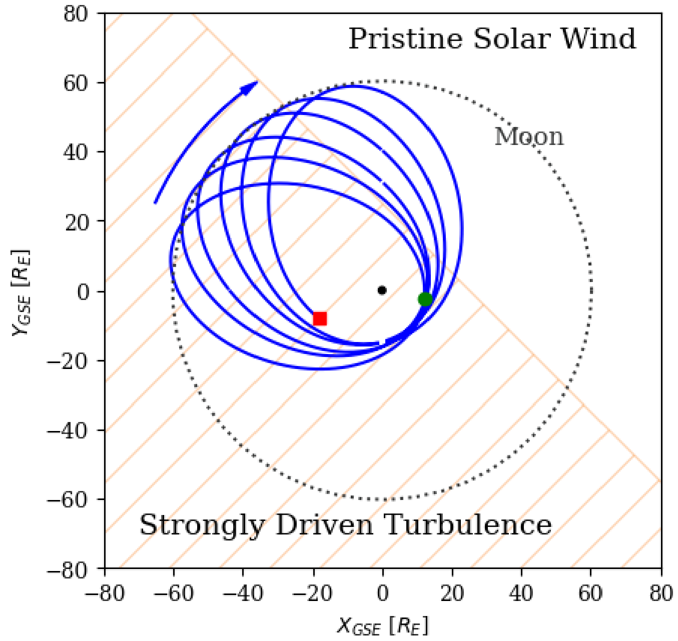
Minimum Hub-Node range for 100 dispersed Node trajectories

(left) 100 dispersed Node trajectories shown in Hub-centered VNC (velocity-normal-conormal) reference frame

Observatory Performance Summary

HelioSwarm Observatory performance measured by total hours accrued in 3D and Polyhedral ("Poly") configurations

- Distinguish between measurements made in the **pristine solar wind** (PSW) and regions of **strongly driven** (SD) turbulence
- 500 hours of 3D and 100 hours of polyhedral configurations required in both PSW and SD regions over full 1-year science mission (~26 revolutions)
- Table below compares Observatory performance with each group of Nodes perturbed (all other Nodes following DRM trajectories) for ~6 revolutions
- Statistics computed on 100 iterations, likely insufficient to fully capture distribution but included for reference



	DRM [hrs]	Perturb Node 1, 2, 5 [hrs]				Perturb Node 3, 4 [hrs]				Perturb Node 6, 7, 8 [hrs]			
		Min	*Max*	*Mean*	*σ*	*Min*	*Max*	*Mean*	*σ*	*Min*	*Max*	*Mean*	*σ*
PSW-3D	99	86	111	99	3.80	92	107	99	2.00	99	99	99	0
SD-3D	556	551	567	557	2.65	550	564	555	2.59	529	564	555	9.80
PSW-Poly	152	108	177	152	11.40	132	166	152	4.62	151	156	153	1.20
SD-Poly	502	464	523	501	10.89	446	507	489	10.47	481	514	503	5.64

Node ΔV

Under dispersions, Node OTMs assume different values from DRM, representing the statistical component of these maneuvers

- Computed 95th percentile ΔV (DV95) from 100 iterations of each perturbed Node (see previous caveat about statistics)
- Difference between DRM and perturbed DV95 illustrates statistical component of swarm maintenance maneuvers
- Large statistical component for Nodes 1 and 3 suggests targeting algorithm modification may be required

Node	DRM [cm/s]	Perturbed [cm/s]	Difference [cm/s]	Percent Difference
1	620	2140	1520	245%
2	373	550	177	47%
3	555	2677	2122	382%
4	815	1250	435	53%
5	408	482	74	18%
6	52	73	21	40%
7	122	142	20	16%
8	74	95	21	28%

Summary and Conclusions

Initial assessment of flight path control error under the influence of maneuver execution error and maneuver planning timeline constraints reveals no critical impacts to Observatory performance

- Observatory science performance degrades by up to ~30% (in terms of science observation hours) over 6-revolution span studied
- While significant, the swarm design philosophy, leveraging natural motion and nearly repeating relative trajectories, has extensive margin to absorb loss of observing hours due to flight path control
- Relative trajectories preserve separation in the presence of perturbations

Node OTMs, particularly for the outer Nodes, have significant statistical components

- Revised targeting algorithms may reduce statistical component

Swarm architecture was selected for HelioSwarm to provide robustness and enable multi-satellite science from a cost-effective mission platform

Swarm philosophy eases requirement on the precision of maneuver planning and execution, relaxing expectations for ground operations turn-around time and accepting performance of extant small satellite propulsion systems