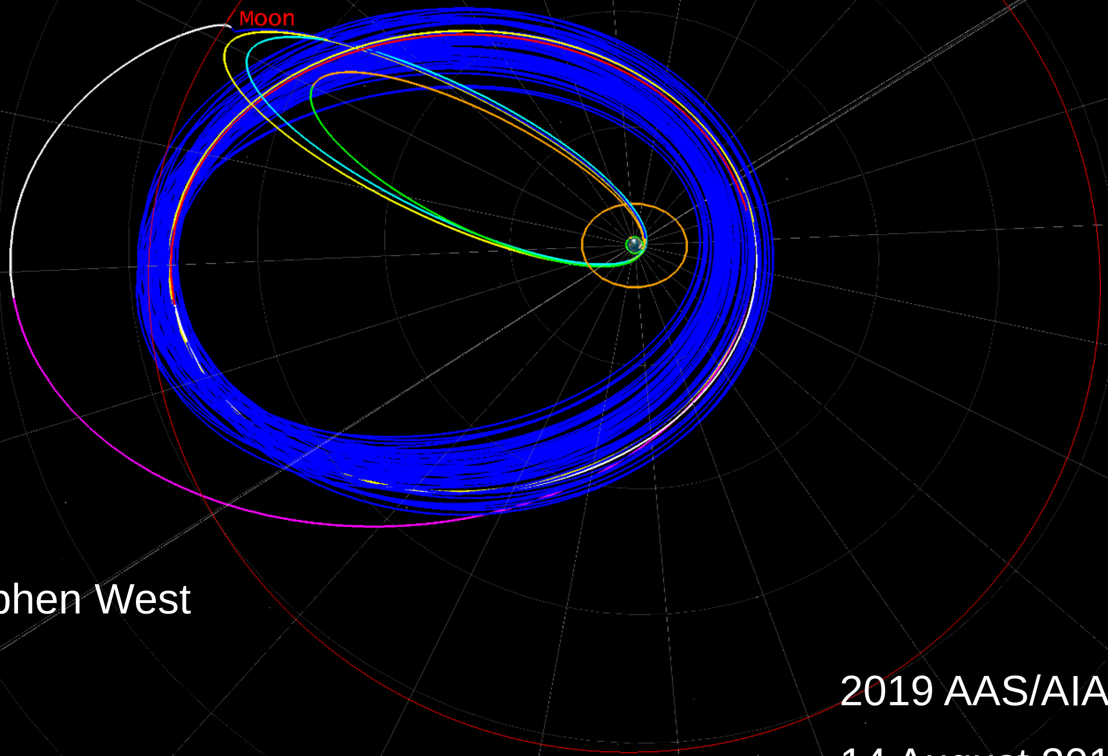
HelioSwarm: Swarm Mission Design in High Altitude Orbit for Heliophysics



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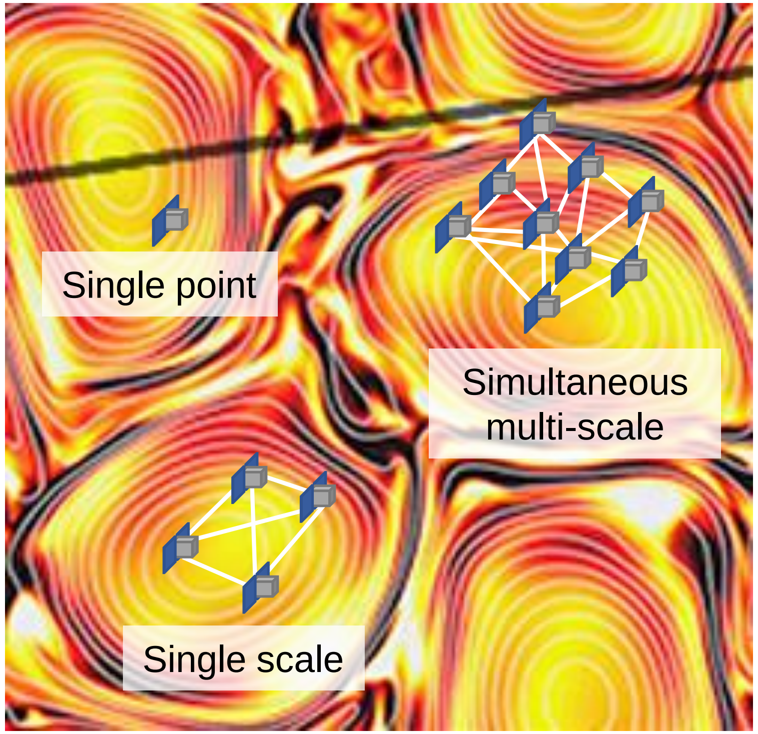
Introduction

- Plasma turbulence is a ubiquitous (and poorly understood) phenomenon throughout the universe
  - Solar wind near Earth is a natural laboratory
- HelioSwarm is a MIDEX-class mission concept to study this process
  - First **simultaneous** multi-scale measurements of plasma turbulence
  - Build upon previous single-point and single-scale (at any given point in time) measurements

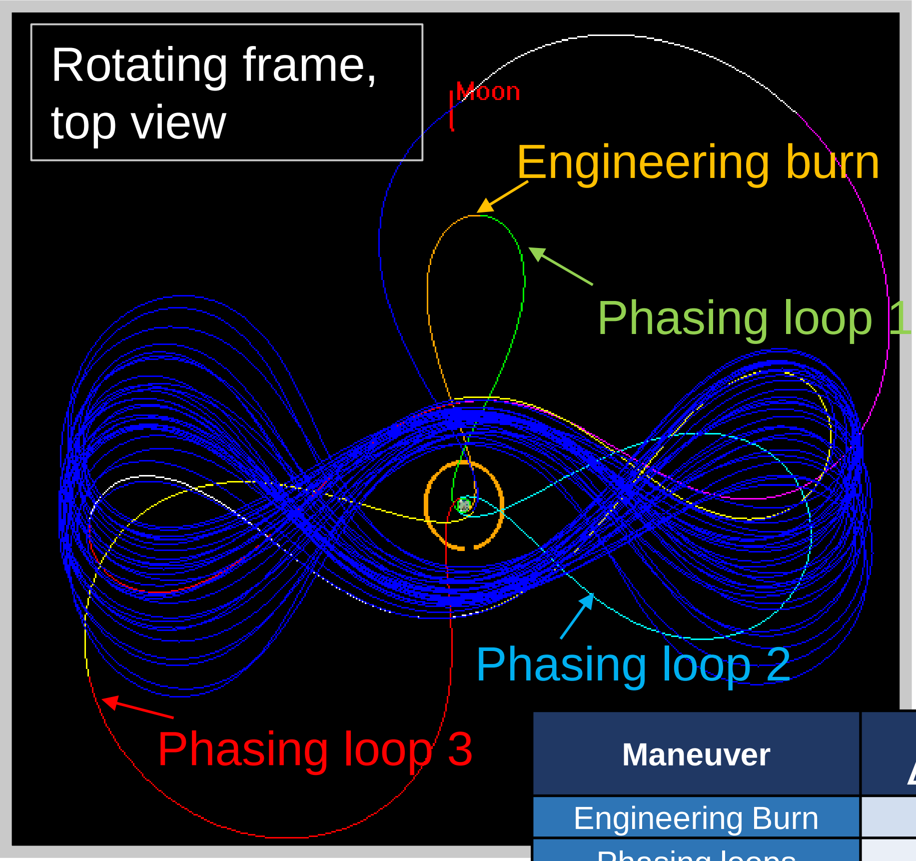


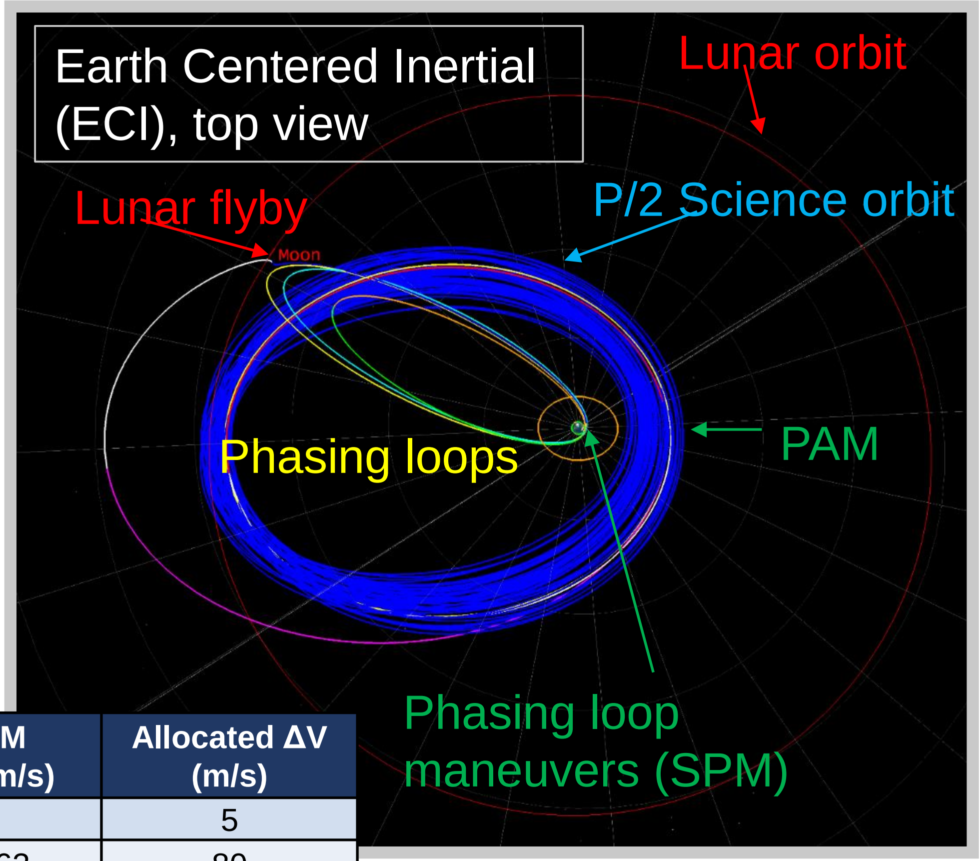
Background image: NASA/J. Dorelli

Mission Design Constraints

- Access the pristine solar wind (HEO)
  - Long term stability for GEO clearance
- Multipoint measurements
  - Baseline science requires 9 spacecraft
  - Cover separation scales of 50-3000 km
- MIDEX-class mission
  - Limitations on operational cadence and complexity
- ESPA-class Node spacecraft
  - Design to performance (eclipses, maneuverability, etc.)

Trajectory Design



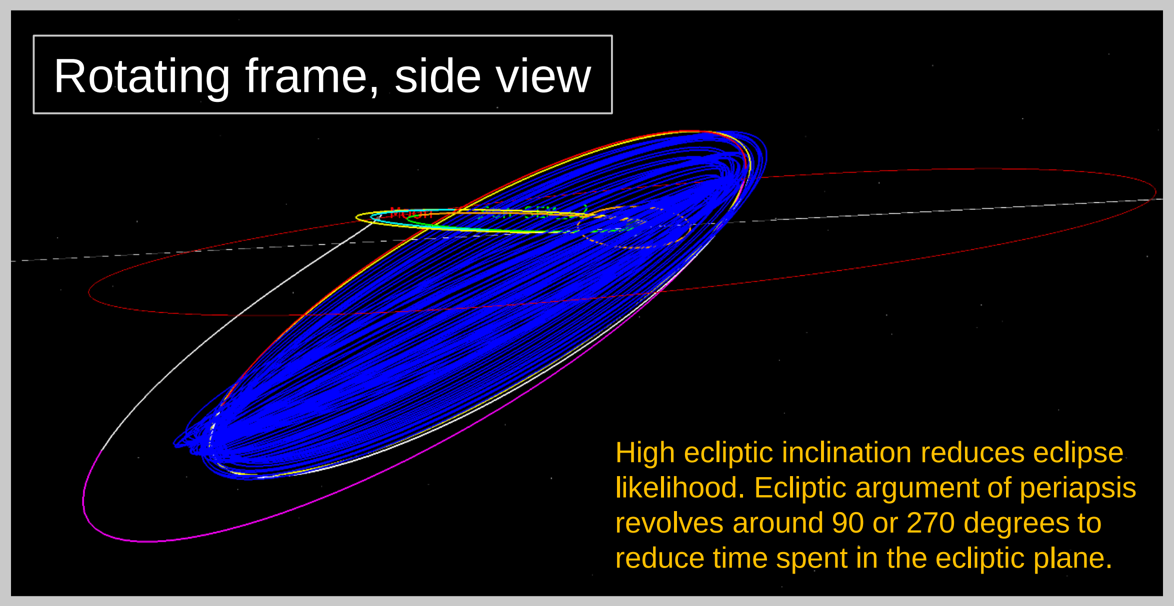


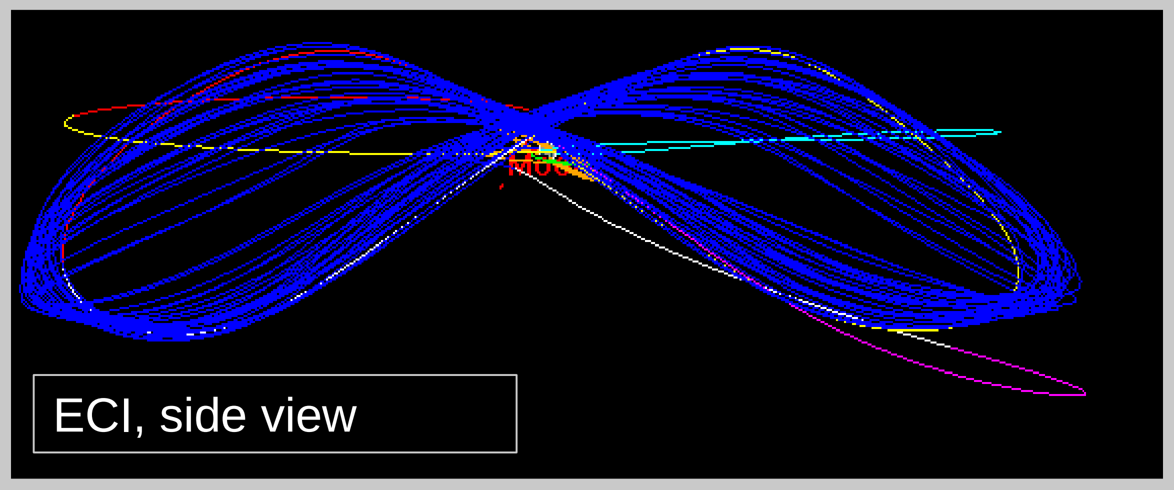
Maneuver	DRM ΔV (m/s)	Allocated ΔV (m/s)
Engineering Burn	2	5
Phasing loops	30.63	80
Launch dates	--	10
Launch window	--	10
PAM	68.63	150
TOTAL	**101.26**	**255**

Science Orbit

P/2 science orbit precesses and orbital elements exhibit slow periodic variation

HS DRM Orbit Element Summary 4 Mar 2026 - 27 Nov 2027				
	min	max	mean	unit
SMA	36.9	38.9	37.9	Re
ECC	0.61	0.77	0.70	-
INC	26.1	50.8	39.3	deg
ARGP	13.8	40.1	23.6	deg
RAAN	309.3	334.3	324.7	deg
INC_ECLP	19.8	31.0	24.4	deg
ARGP_ECLP	33.7	100.3	59.5	deg
RA	61.5	68.0	64.3	Re
RP	8.8	15.2	11.6	Re



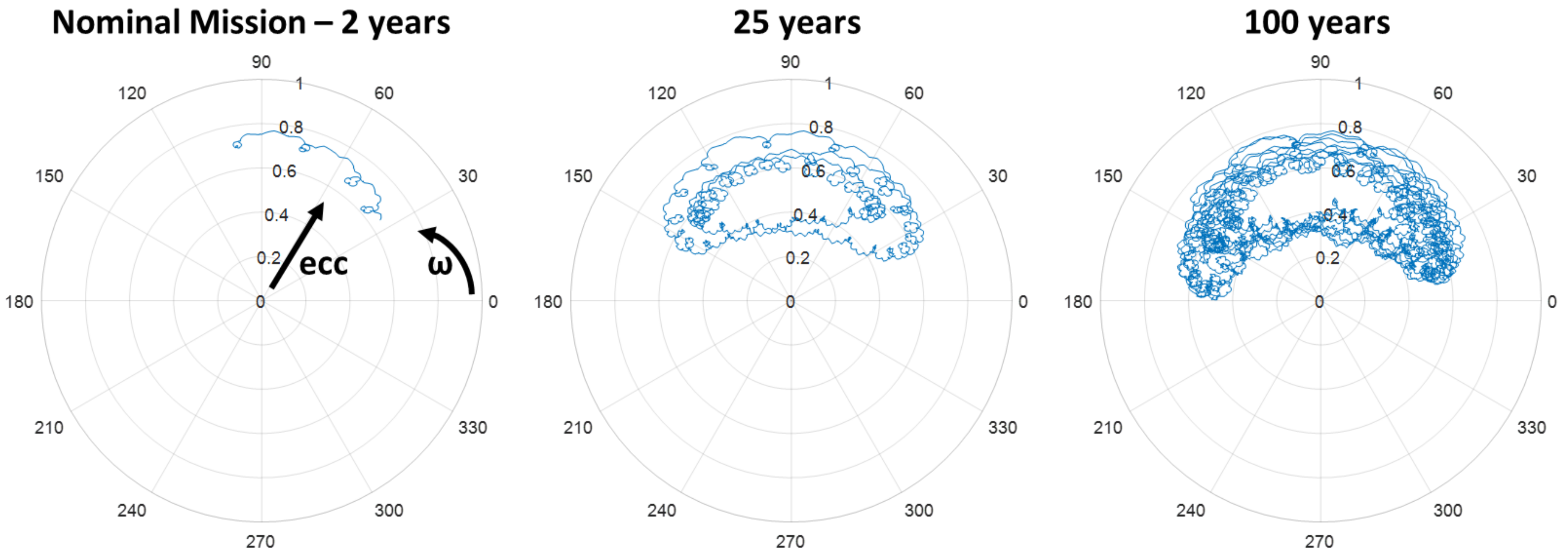


Science Orbit

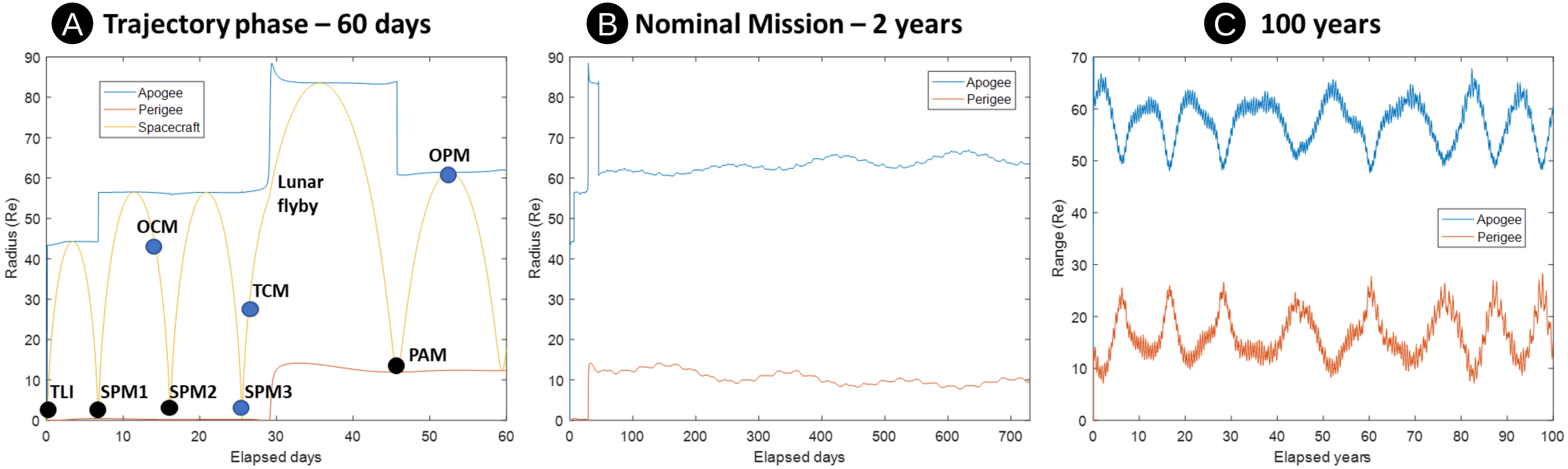
The nominal mission requires specific configuration of eccentricity and ecliptic argument of periapsis.

The signature of eccentricity and argument of periapsis should revolve around 90° or 270° and stay within 0.7-0.8, respectively, to achieve short eclipse durations and orbit stability during the science phase.

Argument of periapsis starts at <90° (~30°) and evolves towards the pole, maintaining low values for the eclipse durations.

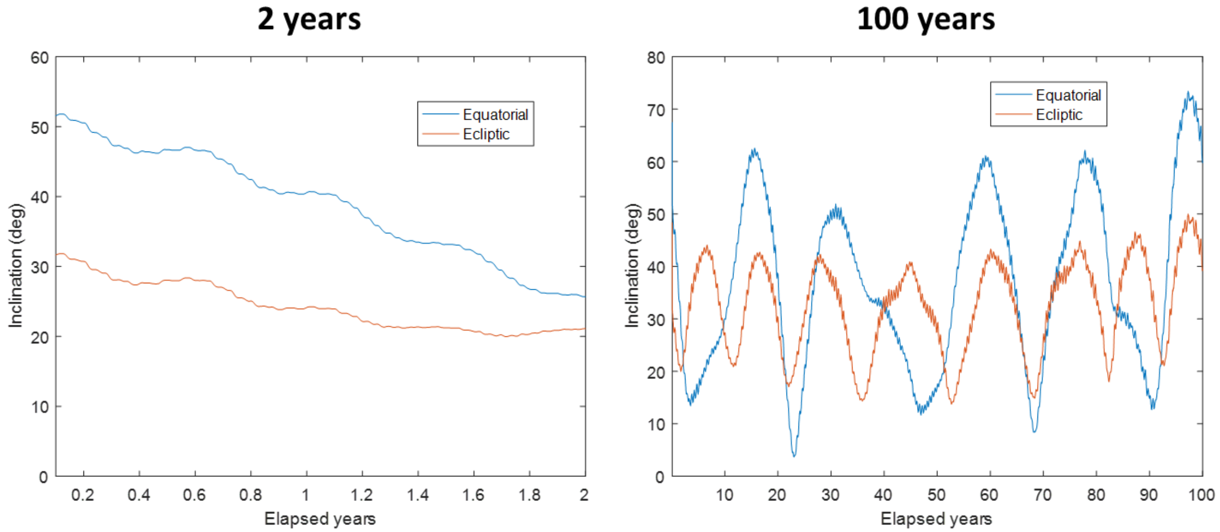


Science Orbit



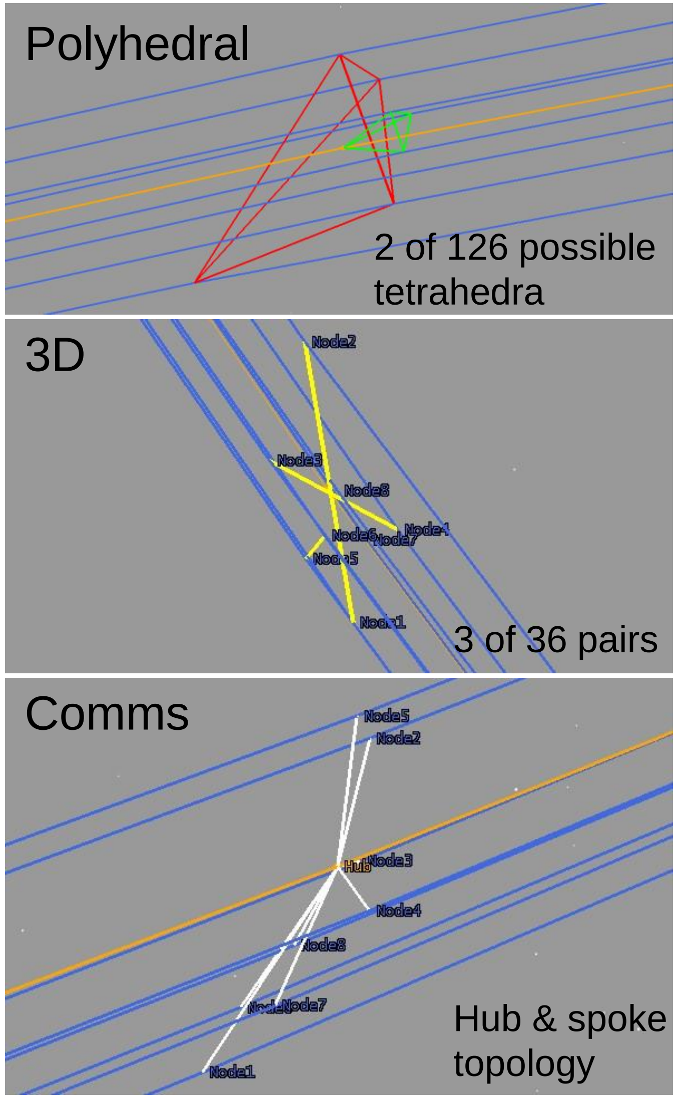
Radius of perigee and apogee during the trajectory phase (A), nominal mission (B), and 100 year propagation (C).

- Black and blue colored dots show the nominal and statistical maneuvers, respectively.
- Nominal mission shows sufficient clearance with respect to GEO.
- 100-year propagation shows a stable configuration, with no GEO crossing.



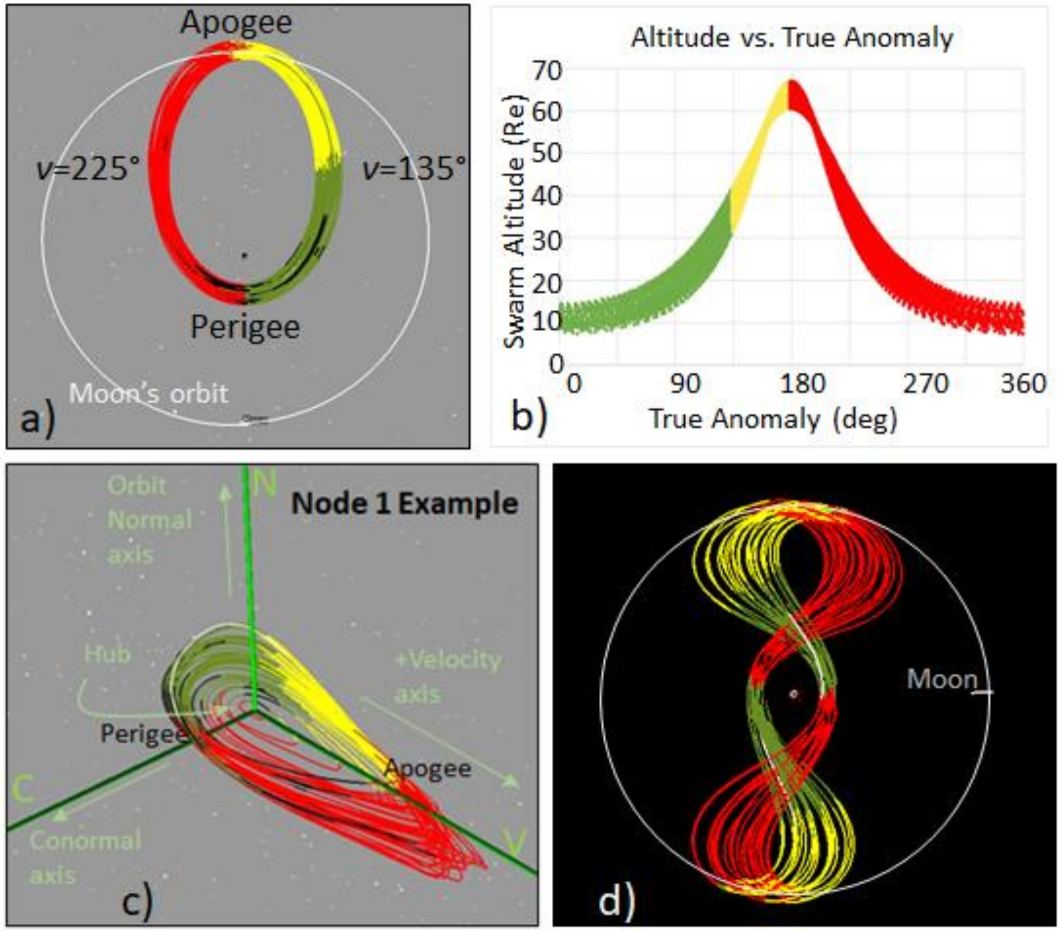
Swarm Design Requirements

- “Polyhedral” requirement
  - Spatial geometries for volumetric analysis techniques
  - Polyhedron quality defined using parameters Elongation (E), Planarity (P), and Size (S), see *Paschmann and Daly (1998)*
  - Satisfied when swarm forms two polyhedra with $\sqrt{E^2 + P^2} < 0.6$ and $\frac{S_1}{S_2} \geq 3$
- “3D” requirement
  - Inter-satellite baseline *components* along three orthogonal axes in 3 spatial bins: 50-100 km, 100-1200 km, and >1200 km
- Communications requirement
  - Reduce separations to for higher crosslink communications rates



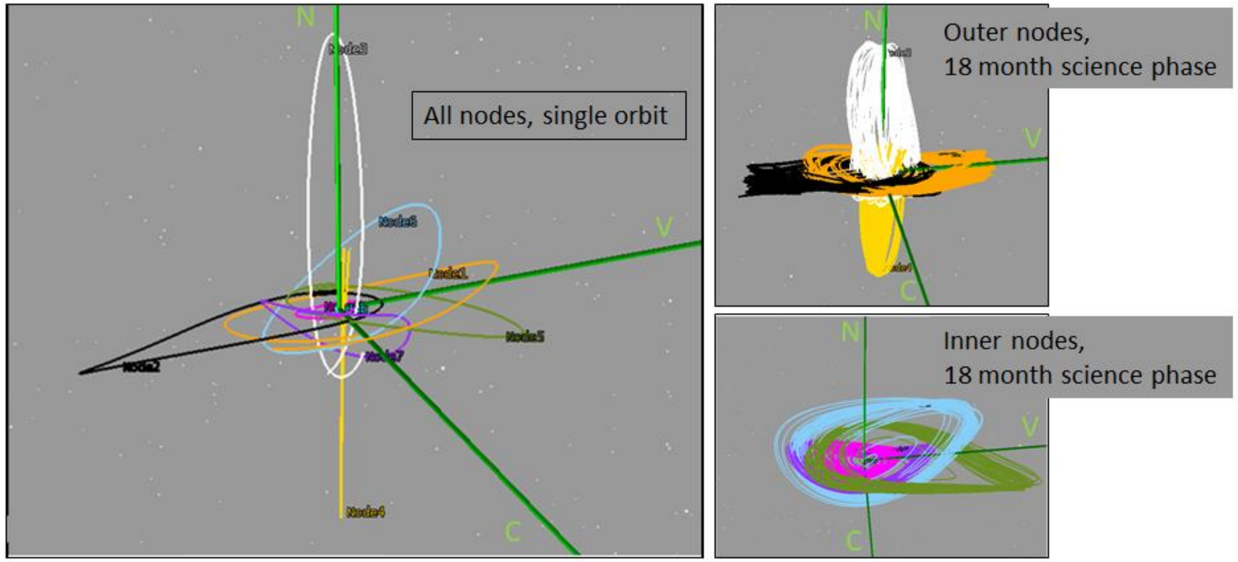
Relative Motion in HEO

- Canonical relative motion (e.g. HCW) analytical techniques do not apply in highly eccentric orbits
- VNC axes used to describe and design swarm relative motion
  - V- and C-axis motion is coupled
  - N-axis motion is independent
  - N- and C-axis motion is periodic
  - V-axis motion triggers large secular, in-track drift
- N- and C-axis impulses are primary inputs for swarm configuration management



Swarm Design Concept

- Four nodes provide baseline components
  - Requirement framed with respect to Sun
  - Maximum separation (near apogee) selected to provide required out of plane components
- Four nodes provide asymmetric (C-axis) components for polyhedra
  - Design for maximum separation to occur off of V- and C-axes
- Six nodes meet baseline science requirements, two provide margin and architectural redundancy



Node	Desired Motion	Target Max. Range from Hub	Maneuver Placement
1	In plane, +V/C	1600 km	TA90
2	In plane, -V/C	1600 km	TA90
3	Out of plane, +N	1500 km	TA90
4	Out of plane, -N	1500 km	TA90
5	Asymmetric, +V/-N/+C	1500 km	TA240
6	Asymmetric, +V/+N/-C	900 km	TA120
7	Asymmetric, +V/-N/-C	700 km	TA120
8	Hub Orbiter	400 km	TA60

Maneuver Targeting

Nested Targeting Objectives:

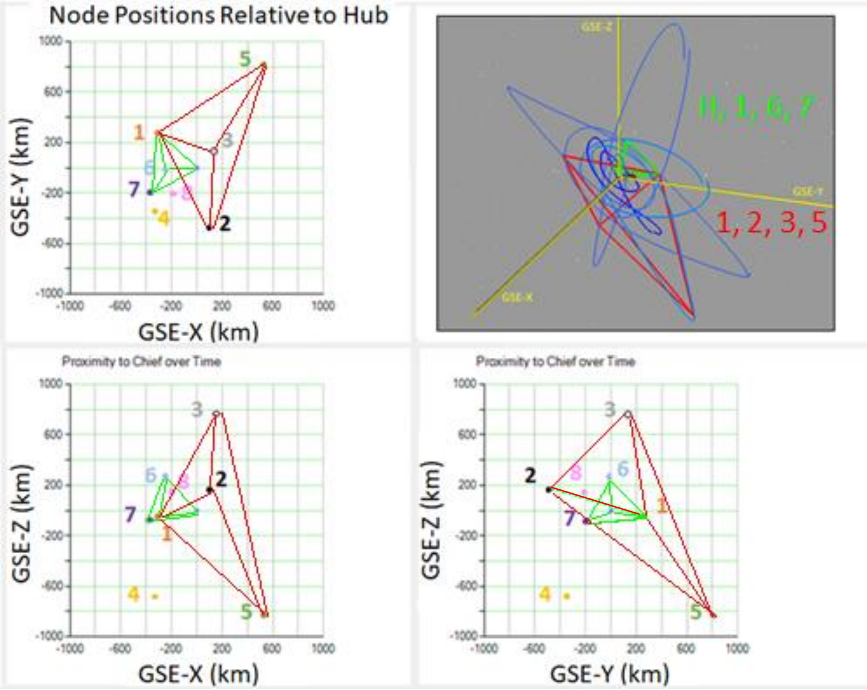
1) Form acceptable polyhedra, reach maximum separations for 3D requirement
2) Stay in phase with other S/C to reach polyhedral/3D configuration at same time
3) Return to Hub vicinity for communications (respecting 10 km KOZ)

Node	DRM ΔV (m/s)			Allocation (m/s)
	SIM	OTM	Total	
1	2.2	25.9	28.1	50.0
2	3.5	19.7	23.2	50.0
3	5.1	13.6	18.7	50.0
4	5.0	10.3	15.3	50.0
5	2.2	18.2	20.4	50.0
6	0.8	13.8	14.6	50.0
7	1.4	10.6	12.0	50.0
8	0.1	10.9	11.0	50.0

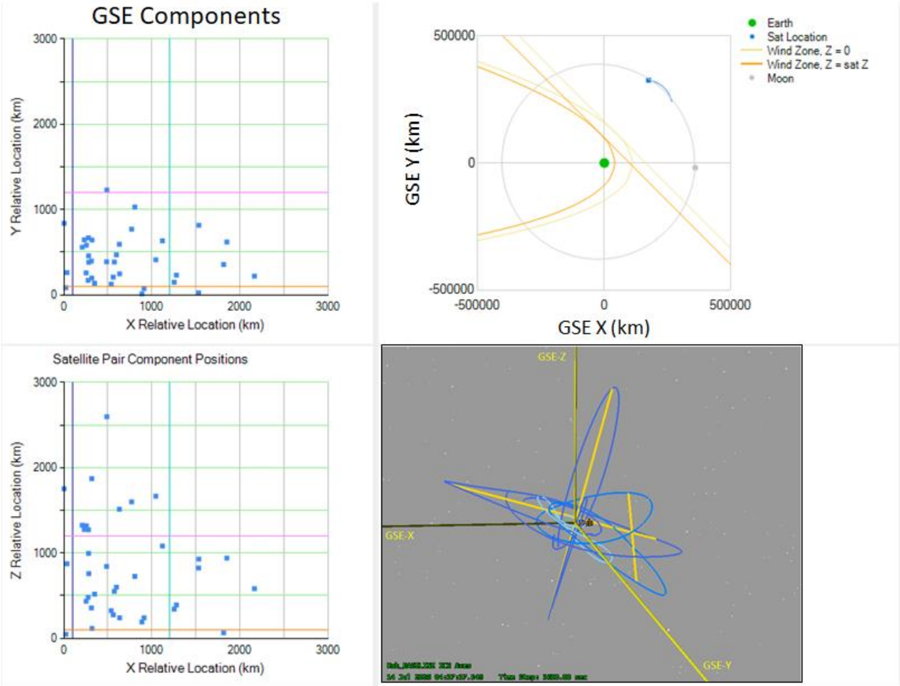
- “Swarm Insertion Maneuvers” (SIMs) increase separation between Node and Hub
  - Initiate relative motion
  - 1-3 SIMs/Node
  - <5.2 m/s
- “Orbit Trim Maneuvers” (OTMs) maintain relative motion
  - Magnitude varies by Node
  - Average magnitude ~0.23 m/s

Swarm Geometry

Internal tools developed to analyze swarm geometry against science requirements



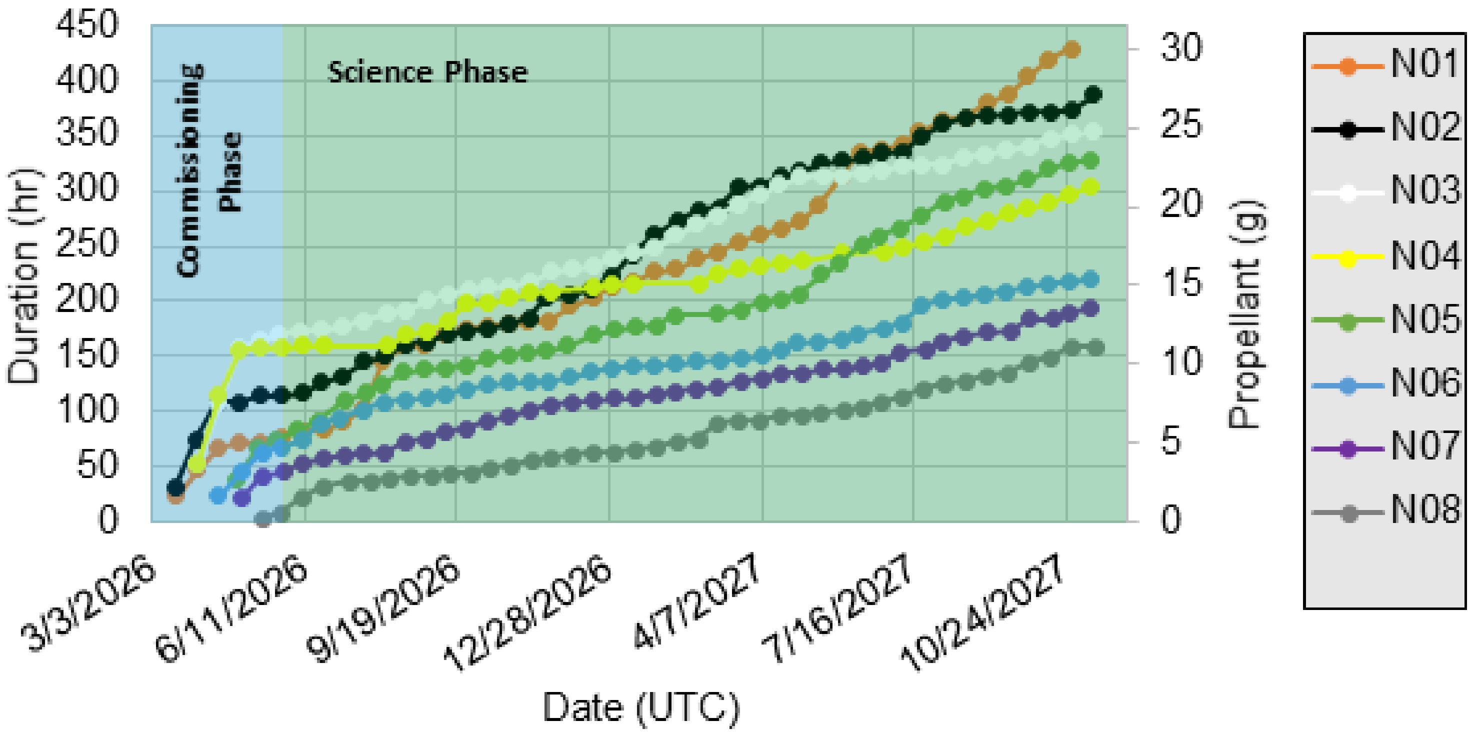
Polyhedral geometries established between 7 nodes



Baseline components fill required magnitude bins along each GSE axis

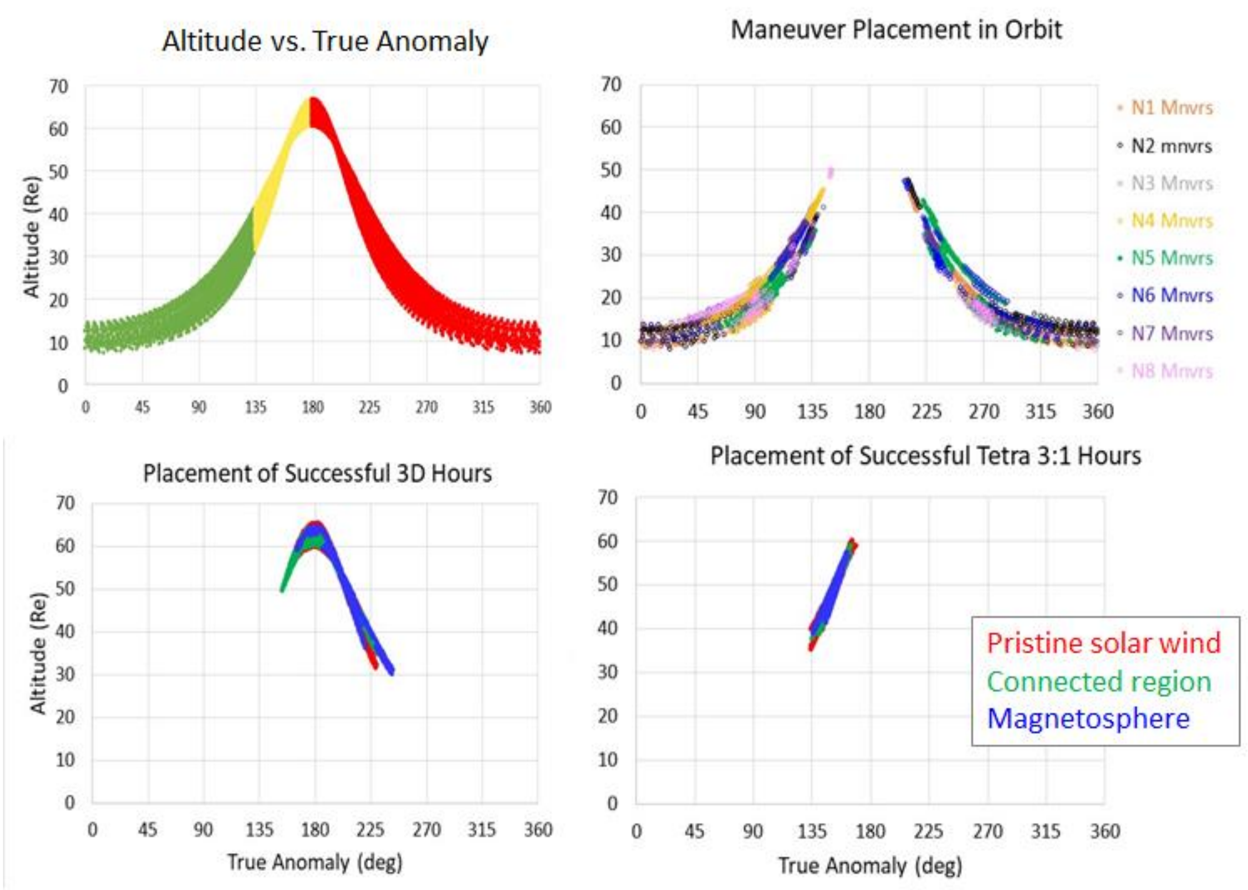
Swarm Maneuvers

- SIMs (largest maneuvers) during commissioning phase
- OTMs regular, small maneuvers throughout science phase
- Cumulative thrust time <500 hrs



Electric Propulsion System: 0.76 mN at 4000 sec Isp

Swarm Performance



Requirement/Region	DRM Performance 8 Nodes	 6 Nodes	Requirement Baseline	 Threshold
3D - Pristine Solar Wind	1576	1012	500	100
3D - Strongly Driven Turbulence	1635	1144	500	100
3D - Total	**3211**	**2156**		
Polyhedral - Pristine Solar Wind	945	519	100	0
Polyhedral - Strongly Driven Turbulence	1037	325	100	0
Polyhedral - Total	**1982**	**844**		

- Swarm meets required durations of each configuration in each solar wind region with ample margin
- Swarm achieves science requirements between TA 135 ° -235°
- Maneuvers concentrated outside the prime science region to minimize disruption

Conclusions

- HelioSwarm mission design leverages high-heritage elements combine in a novel way to enable transformational science
- P/2 lunar resonant orbit provides ideal vantage point for observations of the near-Earth solar wind
- Phasing loops and lunar swing-by enable robust, efficient transfer
- Swarm configuration enables multi-point heliophysics science with single maneuvers each orbit for maintenance