Spacecraft Swarm Missions

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Swarm Technologies

Technological advancements across the small satellite community have enabled new approaches to complex, large scale missions. Multi-spacecraft geometries of constellations, clusters, and swarms are being developed to undertake a variety of defense, scientific, and commercial missions. These missions leverage groups of small satellites working together as a system. This lecture will discuss the technology advancements being used for spacecraft swarm missions, and how those are being deployed, tested, and adopted into future missions. Two missions serve as current examples of the development and use of swarm technology: the Starling Technology Mission and the HelioSwarm Science Mission. Starling is a technology demonstration mission launched last year and flying in space now testing key swarm technologies. HelioSwarm, currently in development, is a multi-spacecraft swarm science mission that will transform our understanding of space plasma turbulence. These are pathfinding missions that enable future large scientific and commercial swarms

Constellations vs. Swarms

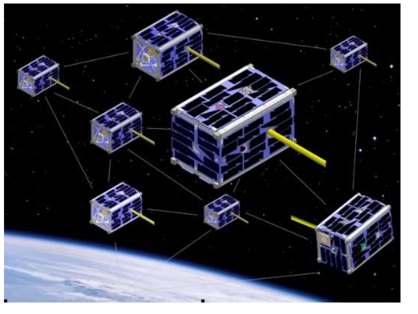
Constellation

- Multiple (small group) spacecraft in different orbits
- Each spacecraft is **individually controlled** by ground (expensive and limited performance)
- Spacecraft can exchange data, but do not necessarily have knowledge about each other's motions and movements
- Examples: GPS, Iridium, etc

Constellation

Swarm

- Multiple (large group) spacecraft that may operate in close proximity and require spatial configuration
- Swarms can **actively work as a "collective"** to accomplish a common task:
  - Distributed, multi-point measurements
  - Redundancy (spatial coverage, comm, etc.)
- Various configurations: same orbit (with in-train gap), constrained ellipse (no active control), fixed formation



Swarm

Enabling Swarms: The Problem

Current state-of-practice allows satellite groups to be implemented using ground control of individual spacecraft.

- Used in existing constellations
- Scaling operations to large sets of spacecraft is “operations” cost prohibitive.
- Maintaining a desired swarm configuration often needs rapid corrections, driving operations requirements.

Enabling very large swarms (e.g. 30-100 spacecraft) suggests the swarm be operated as a ‘single unit’.

- High-level only commanding from the ground
- The swarm must maintain its own configuration to achieve the ground-commanded goals.

Enabling Swarms: Technologies

The core technologies enabling swarms are a mixture of mature in-space, mature on-the-ground, and new to-be-developed:

Knowledge – How do we know the positions and movements of the spacecraft in the swarm?

Communications – How do we get information to and from the spacecraft in the swarm?

Control – How do we maintain the configuration of spacecraft in the swarm?

Operations – How do we command the swarm configuration and return data from it?

Access – How do we get the swarm into space and deploy it?

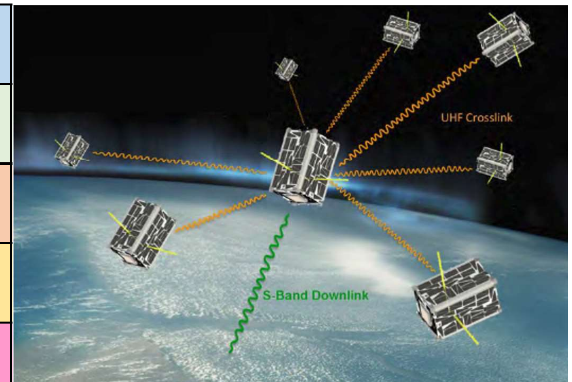
We know how to do all of these with small swarms and traditional operations, but not how to do it cost effectively for large swarms.

Swarm Technology Development Strategy

"Many high-priority science investigations of the future will require data from constellations or swarms of 10 to 100 spacecraft that, for the first time, would have the spatial and temporal coverage to map out and characterize the physical processes that shape the near-Earth space environment." – Achieving Science with CubeSats: Thinking Inside the Box (2016 NAS/SSB Report)

Swarm Technology Components

Knowledge	How do we know the positions and movements of the spacecraft in the swarm?
Communications	How do we get information to and from the spacecraft in the swarm?
Control	How do we maintain the configuration of spacecraft in the swarm?
Operations	How do we command the swarm configuration and return data from it?
Access	How do we get the swarm into space and deploy it?

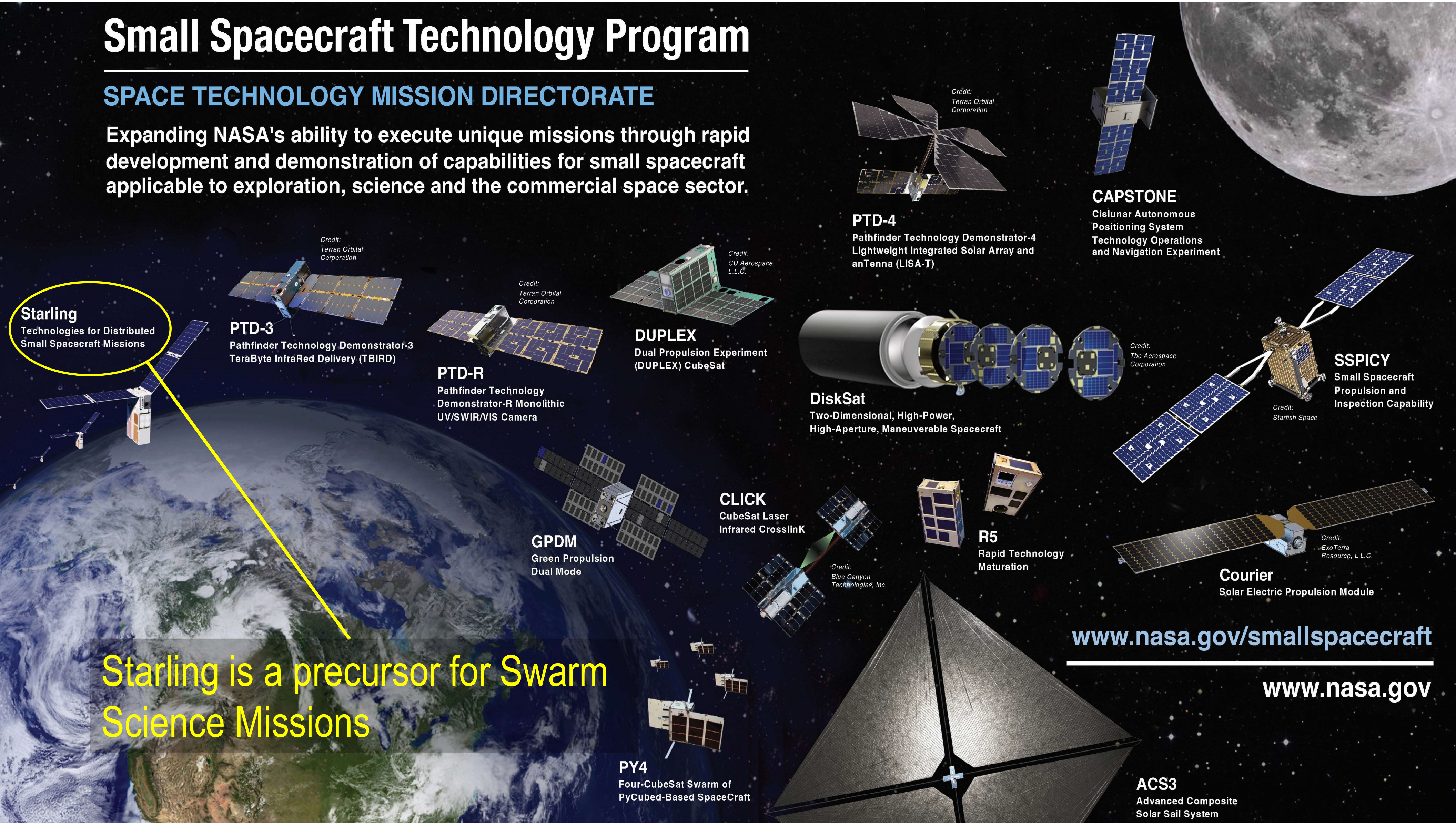


End Goal: Enable Swarm Technologies for future science missions

Previous Missions: NODES, OCSD, CPODS

Technology Demonstration Missions (LEO)

Mission 1		Mission 2		Mission 3	
	Ground, GPS, JSPOC and dGPS		RF & Optical Ranging, Optical Imaging		RF RADAR, Optical LIDAR
	RF		RF & Optical		RF & Optical
	RW & MT		Propulsion (cold-gas) and Differential Drag		Propulsion (chemical) and/or Electric
	RF		Command & Maintain swarm configuration		On-board Nav with Ground-in-Loop
	Low-precision deployment		High-precision deployment (time)		High-precision deployment (time & separation)



Small Spacecraft Technology Program
SPACE TECHNOLOGY MISSION DIRECTORATE
Expanding NASA's ability to execute unique missions through rapid development and demonstration of capabilities for small spacecraft applicable to exploration, science and the commercial space sector.
Starling
Technologies for Distributed Small Spacecraft Missions
Credit: Terran Orbital Corporation
PTD-3
Pathfinder Technology Demonstrator-3 TeraByte InfraRed Delivery (TBIRD)
Credit: Terran Orbital Corporation
PTD-R
Pathfinder Technology Demonstrator-R Monolithic UV/SWIR/VIS Camera
Credit: CU Aerospace, L.L.C.
DUPLEX
Dual Propulsion Experiment (DUPLEX) CubeSat
Credit: Terran Orbital Corporation
PTD-4
Pathfinder Technology Demonstrator-4 Lightweight Integrated Solar Array and anTenna (LISA-T)
CAPSTONE
Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment
Credit: The Aerospace Corporation
DiskSat
Two-Dimensional, High-Power, High-Aperture, Maneuverable Spacecraft
SSPICY
Small Spacecraft Propulsion and Inspection Capability
Credit: Starfish Space
GPDM
Green Propulsion Dual Mode
CLICK
CubeSat Laser Infrared CrosslinK
Credit: Blue Canyon Technologies, Inc.
R5
Rapid Technology Maturation
Credit: ExoTerra Resource, L.L.C.
Courier
Solar Electric Propulsion Module
www.nasa.gov/smallspacecraft
www.nasa.gov
Starling is a precursor for Swarm Science Missions
PY4
Four-CubeSat Swarm of PyCubed-Based SpaceCraft
ACS3
Advanced Composite Solar Sail System

The Starling Mission

NASA Ames – Spacecraft Swarms

NASA Ames has been working on enabling the vision of spacecraft "swarms" > 10 years.

- Spacecraft Swarms:
  - Groups of spacecraft **cooperating with each other** to achieve a goal
  - Acts as a **single unit** versus needing to command and control each spacecraft separately
  - Include **autonomy** so that they can change behavior based on engineering or science measurements
- Advantages:
  - Multi-point science data collection (e.g. Helioswarm)
  - Improved overall robustness due to systems redundancy
  - Potential for upgrades by adding additional spacecraft to the swarm
  - Reduced communication needs for large group of spacecraft
  - Enables opportunistic science

Starling is a mission to test and demonstrate key technologies that are essential to this vision.

Starling Project Summary

Project Summary

- NPR 7120.8 Research and Technology Project
- Starling will fly 4 x 6U spacecraft in LEO
- Launch via Rocket Lab Electron (Summer, 2023)
  - 575km, sun-synchronous orbit
  - 6-month mission ops for original swarm technology experiments
- The Starling mission will test multiple swarm technologies
  - Reconfiguration and Orbit Maintenance Experiments Onboard (ROMEO)
  - Mobile Adhoc Network (MANET)
  - Starling Formation-Flying Optical Experiment (StarFOX)
  - Distributed Spacecraft Autonomy (DSA)
- Mission extension to Starling 1.5 via software upload to demonstrate autonomous collision avoidance with SpaceX Starlink constellation
- Funding
  - Space Technology Mission Directorate (STMD)
    - NASA Small Spacecraft Technology (SST) Program
    - NASA Game Changing Development (GCD) Program - DSA Experiment

Swarm Technologies in Starling

Network communication protocols:

(MANET – Crosslink/Networking)

- Autonomously map the network topology
- Implement BATMAN networking protocol and demonstrate onboard network management (scalable to 100s of spacecraft)

Cluster flight control algorithms:

(ROMEO – Onboard Cluster Flight Control)

- Autonomously reconfigure and maintain relative vehicle positions (e.g., GPS, ADCS, Prop)
- Implement Cluster Flight Application (CFA) in payload software and demonstrate automated cluster station-keeping

Relative navigation algorithms:

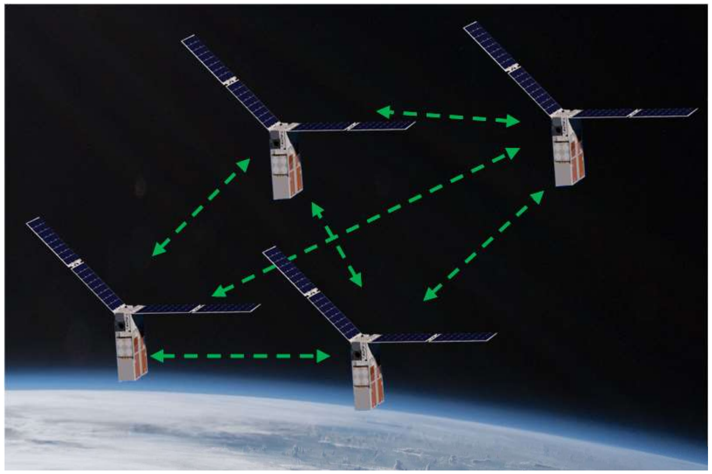
(StarFOX –Relative Navigation)

- Continuously estimate relative vehicle positions using standard spacecraft optical components (i.e., star trackers)
- Implement Stanford's relative navigation algorithms in payload software and demonstrate for both in train and passive safety ellipse formations

Autonomous reactive operations software:

(DSA – Distributed Spacecraft Autonomy)

- Autonomously reconfigure science measurement strategy in response to sensor data
- Detect Total Electron Count (TEC) using bus L1/L2 GPS receiver and have swarm autonomously change observation tactics



The intent was to test each technology to understand what works, what are the limitations, and what is still needed in terms of swarm technology development.

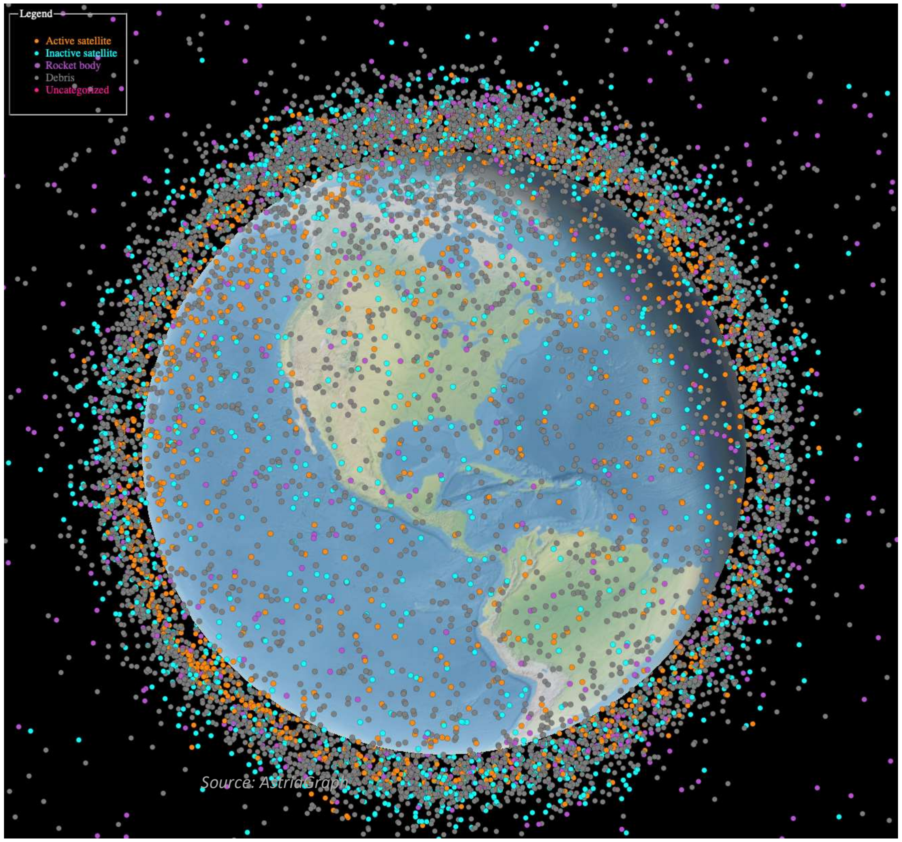
Starling 1.5 Extended Mission

Goal: Demonstrate enhanced space traffic management between different owner/operators of Low Earth Orbit (LEO) spacecraft

- Partner with SpaceX's Starlink constellation to demonstrate coordinated conjunction assessment and collision avoidance

Current State-of-the-Art

- 18th Space Defense Squadron predicts conjunctions and issues warnings to owner/operators when a conjunction event passes a threshold
- Coordination via phone/email to arrive at a course of action
- Does not scale with the number of satellites being put into LEO including those with autonomous maneuvering



Objectives:

- Starling will demonstrate onboard CA:
  - Continuous checking of passive/active maneuvering objects
  - Planned Maneuvers
- Demonstrate a ground-based space situational awareness (SSA) / space traffic management (STM) hub that facilitates on-orbit autonomous CA/COLA
- Demonstrate collision avoidance (COLA) maneuver of Starling spacecraft in response to an onboard CA detection

Starling 1.5 Demonstration Overview

- Satellites calculate Probability of collision (Pc) for conjunctions
- If high Pc event, plan collision avoidance (COLA) maneuvers
- Perform COLA maneuver once screened through the Ground Hub
- Maneuver responsibility claims and future trajectory intentions shared via Ground Hub
- Automates maneuver acceptance through the Ground Hub, rather than requiring operator-to-operator negotiation

Image Source: SpaceX

Updated Orbit States
Proposed Maneuvers

Update Orbit States
Proposed Maneuvers

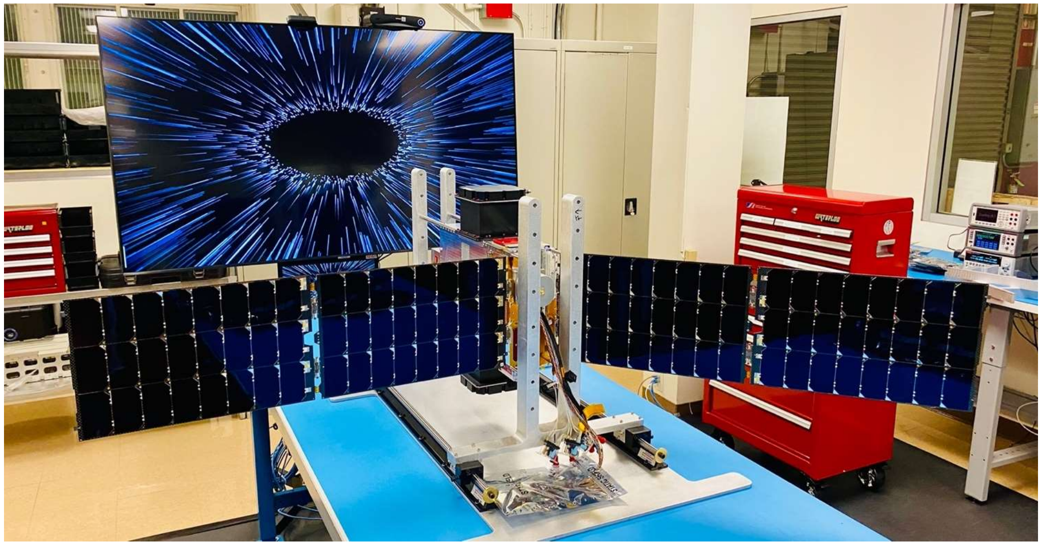
Conjunction Data Messages (CDMs)
Maneuvers Accepted/Rejected

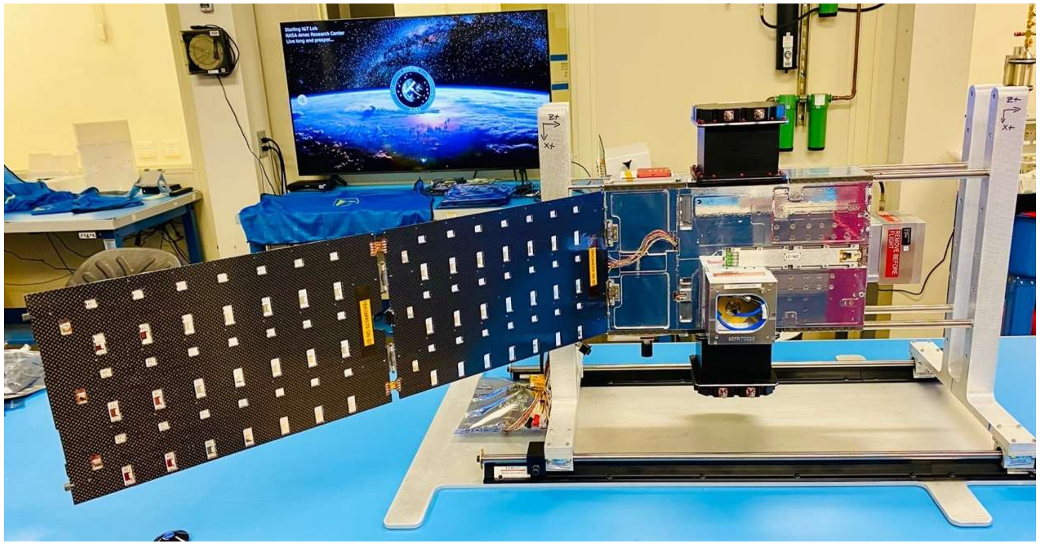
Conjunction Data Messages (CDMs)

STM Ground Hub

- Receives planned trajectories from Starling/Starlink
- Provides CDMs w/ Pc for Starling/Starlink
- Tracks maneuver responsibility claims between owner/operators

Spacecraft Hardware





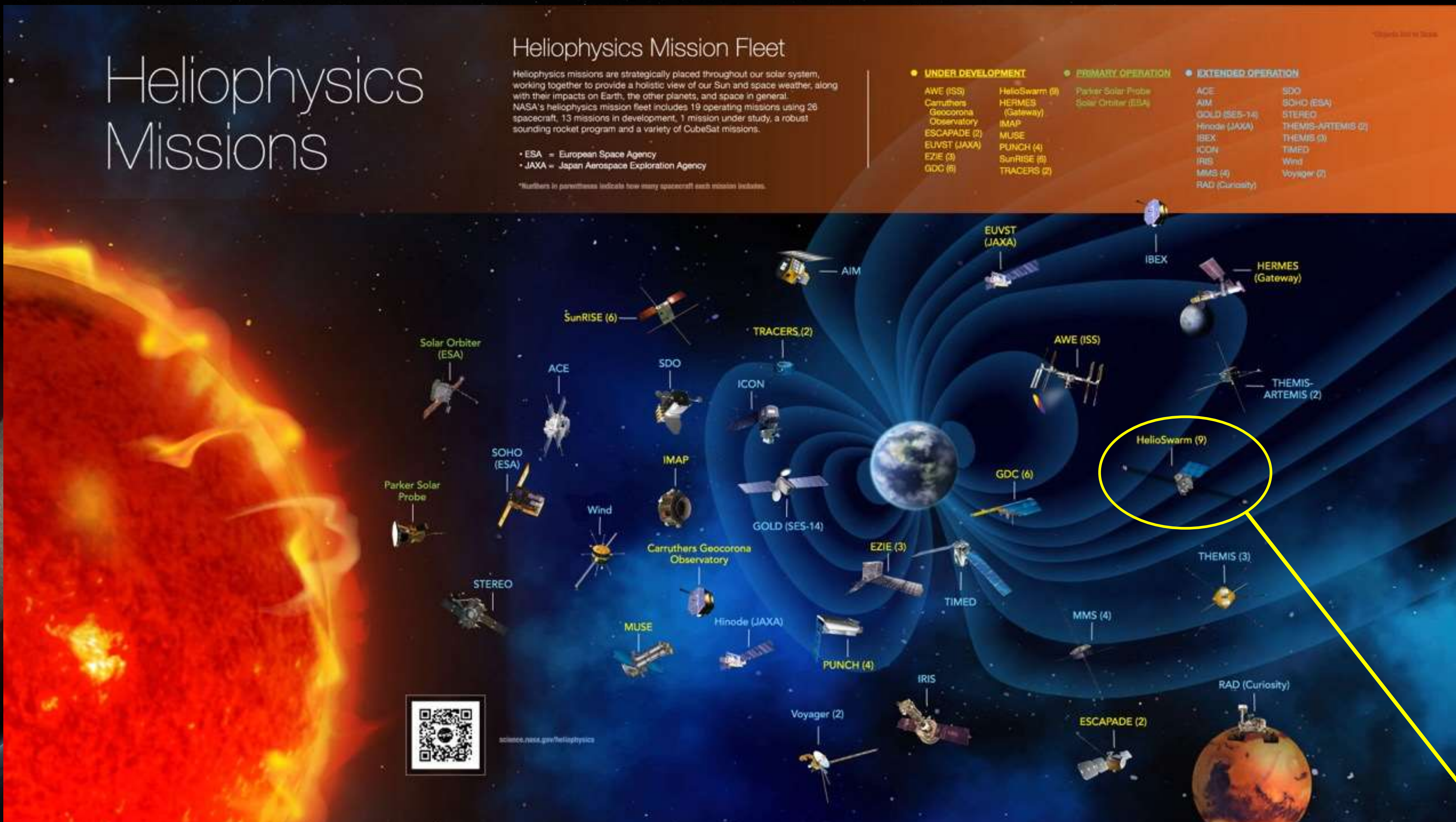
Spacecraft Hardware

Dispenser Integration

Integrated onto the Kick Stage

Launch

- Launch provided by Rocket Lab USA Inc.
  - Launch Vehicle: Electron
  - Launch Facility: Rocket Lab Launch Complex 1, Mahia NZ
  - Launch Date: July 18, 2023
  - Primary Mission Operations: July 2023 – May 2024
  - Current Status: Continues to Operate in Extended Mission



Starling is a precursor for the Helioswarm Mission

HELIO SWARM

THE NATURE OF TURBULENCE IN SPACE PLASMAS

A Multispacecraft Mission to Study Turbulence in Space Plasmas

University of New Hampshire · Ames Research Center · Northrop Grumman · Smithsonian · LPP · irap · LAB · Imperial College London · LPC2E · Goddard Space Flight Center

Mission Overview

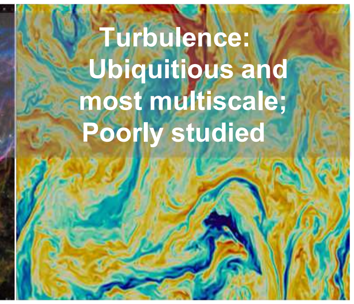
HelioSwarm will transform our understanding of space plasma turbulence, a current high scientific priority, using an innovative mission concept to collect data on multiple physical scales simultaneously

- **Org:** PI-led University of New Hampshire (UNH), managed by NASA Ames Research Center (ARC).
- **Sponsor**: SMD / Explorers Program (GSFC). Medium Class Explorer – MIDEX (Cat II/Class C)
- **Spacecraft:** One central Hub (ESPA-class, Northrop Grumman, NG), Eight co-orbiting Nodes (SmallSats, Vendor TBD) released from Hub once in Science Orbit.
- **Instruments**: Each spacecraft carries two magnetometers (MAG & SCM), one on each of two booms, and a Faraday Cup (FC); the Hub also carries an Ion Electrostatic Analyzer (iESA) and Student Electron Electrostatic (SEE) spectrograph.
- **Orbit:** High Earth Orbit (HEO) with perigee ~13 R_E (~80,000 km) and apogee: ~63 R_E (~400,000 km) with ~13.7-day period.
- **Spectrum**: Hub-and-spoke communications architecture; Hub-Ground uses X-band, Hub-Node links use S-band.
- **Ground Networks:** Deep Space Network (DSN) and Space Relay (SR) / Tracking and Data Relay Satellite System (TDRSS).
- **Operations:** Mission Operations Center (MOC) @ NASA ARC, support centers @NG and Node Vendor (TBD), Science Operations Center @ UNH.
- **Launch:** Targeted for early 2029.
- **Duration:** 12-month Science Phase, 18-month mission.

Background: Resolving Turbulence Across Scales

The majority of visible matter in the universe is plasma: Stars (Sun), stellar (solar) winds, interstellar medium, accretion disks, etc.....

Three universal plasma physics processes govern all these systems:



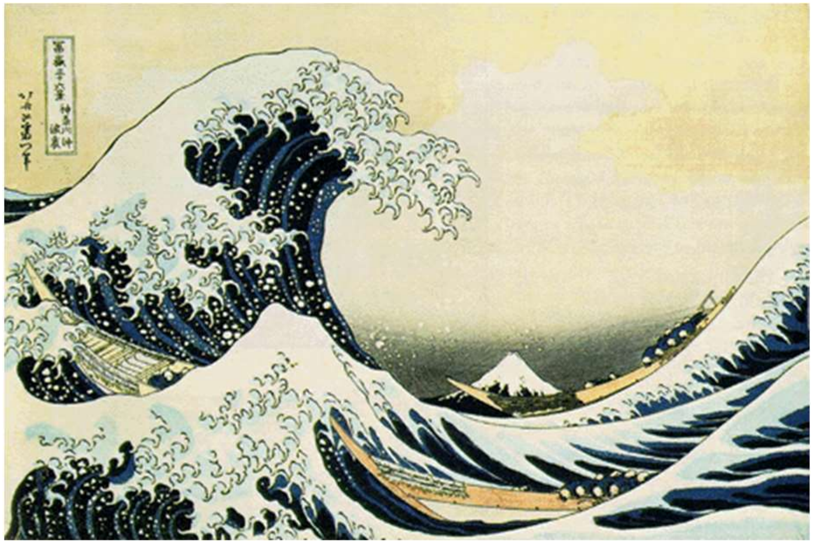
These plasma processes are all highly dynamical, involving couplings between vastly separated scales, ranging from fluid (MHD) scales to microphysical (electron) scales – <u>understanding requires multipoint cross-scale measurements of the plasma physics</u>

Multipoint, cross-scale measurements of heliospheric plasmas needed to test directly unresolved turbulence theories applicable throughout the universe

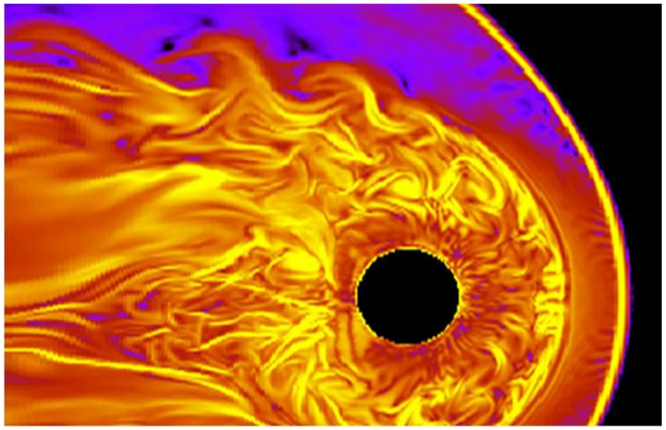
HelioSwarm provides first cross-scale measurements to transform our understanding

What is Turbulence?

- Turbulent flow is one in which a gas, fluid, or plasma undergoes irregular fluctuations and mixing
- Quantifying Turbulent processes is considered by many to be the last unsolved mystery of classical physics
- **Turbulence plays a fundamental role driving the transport of mass, momentum, and energy in a wide variety of kinds of plasmas in our solar system and throughout the Universe.**



Katsushika Hokusai,
Thirty-six views of Mt. Fuji.



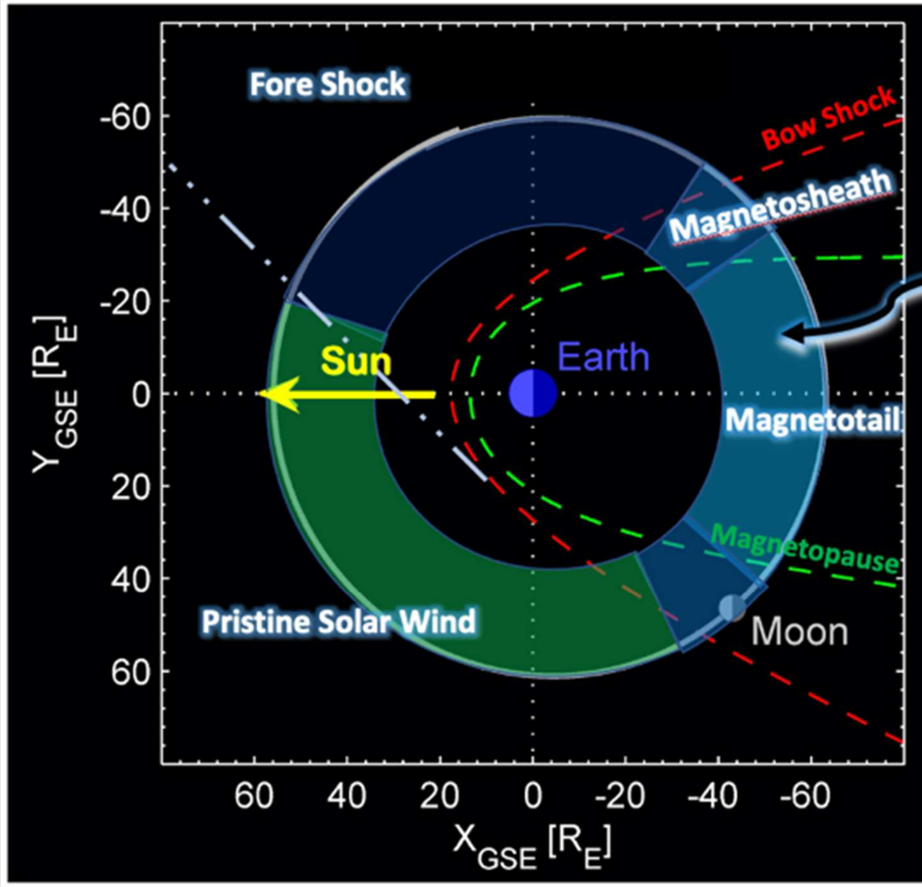
OpenGGCM MHD simulation of Earth's magnetosphere, S. Kavosi, J. Raeder

HelioSwarm's Targeted Science Regions

HelioSwarm covers 3 target regions over the course of one year in orbit

Pristine solar wind is primary mission target as it is the region that addresses 4 of the 6 science objectives; a 5th objective will be explored when the pristine solar wind is impacted by structures (collectively the green shaded region)

The 6th objective will be explored when HS passes through the foreshock, magnetosheath, and magnetospheric regions (collectively the blue shaded regions)

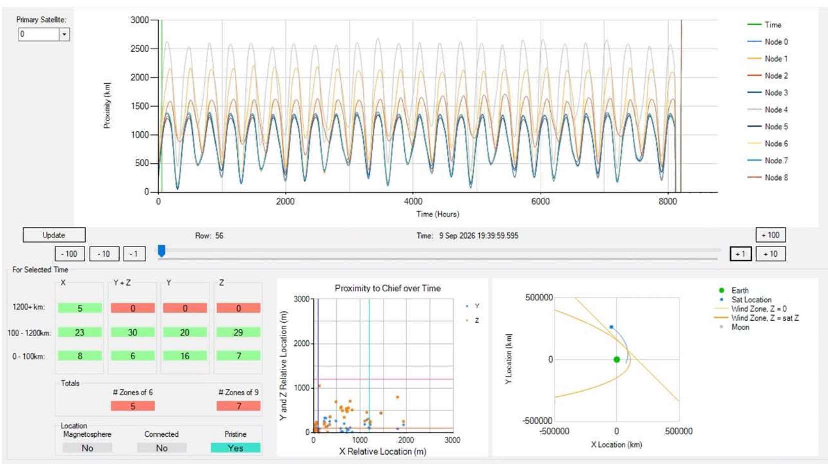


Cartoon showing locations of 3D and polyhedral configurations needed for science closure, produced annually in annular ring proximate to apogee near lunar distances, relative to regions of pristine solar wind and to driven regions (foreshock, distant magnetosheath, distant magnetotail)

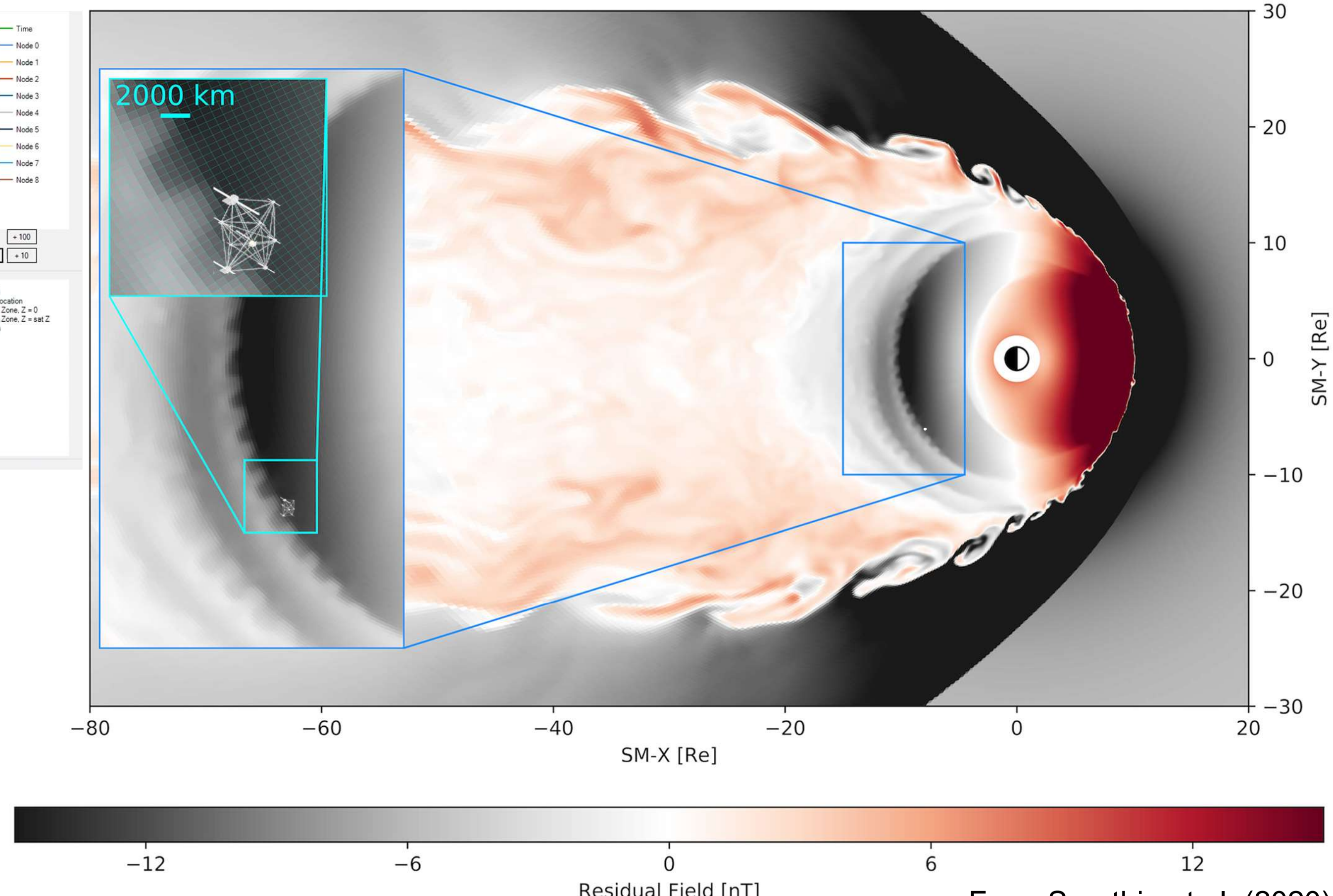
Background Image Credits: Tim Stubbs, Yongli Wang, LRO/LOLA, NLSI/DREAM

Not Just About the Solar Wind

meets



HelioSwarm outer scale: ~3000 km
HelioSwarm inner scale: ~50 km



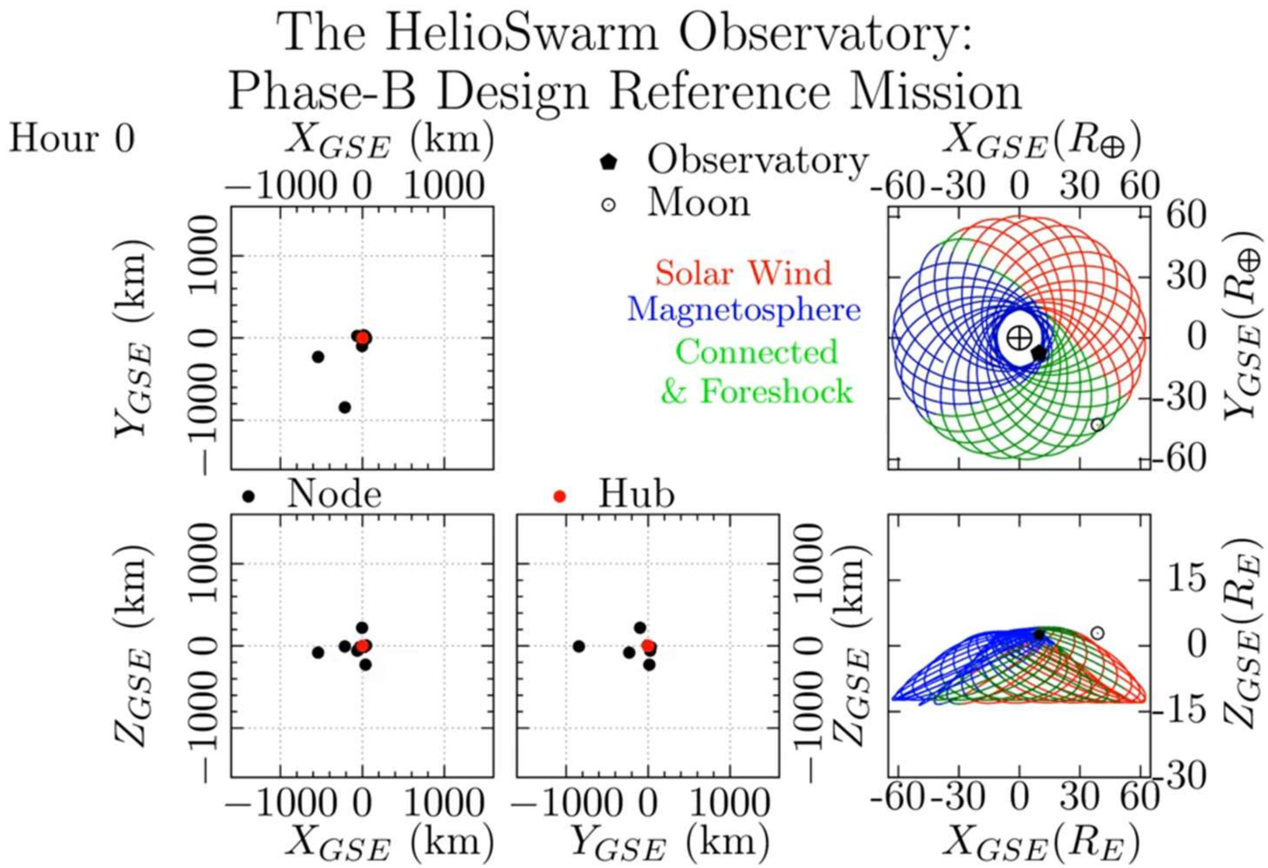
From Sorathia et al. (2020)

Global magnetosphere MHD models like GAMERA can profitably use HS observatory measurements to parameterize and include sub-grid physics at or just below the current state-of-the-art

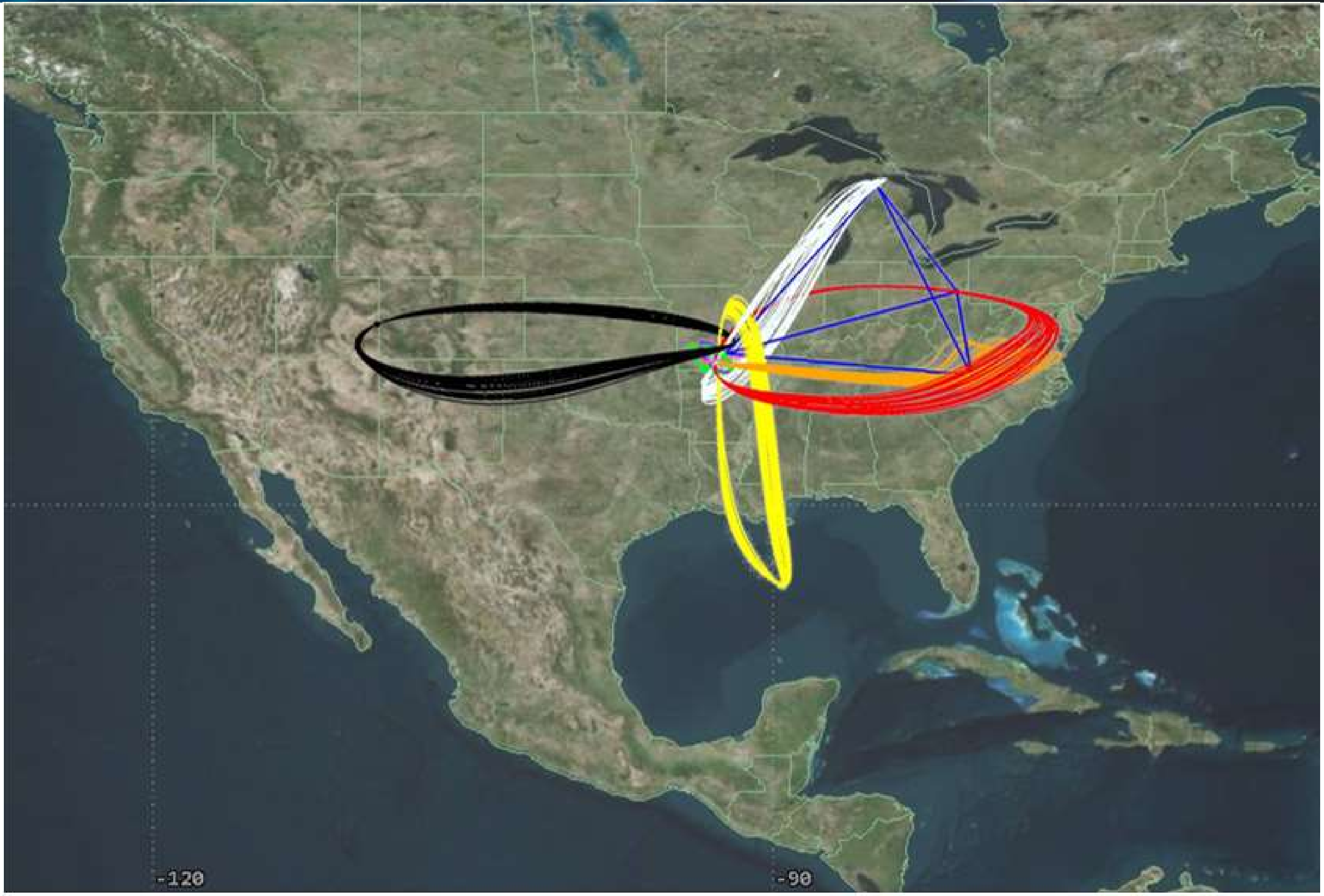
The HelioSwarm Mission

HelioSwarm overcomes the limitations of approximations central to using data from single-spacecraft or single-scale missions, providing a complete space-time measurement of the underlying turbulent dynamics from fluid to ion scales in a variety of near-Earth plasma environments over each two-week orbit.

All Science Measurements are telemetered to the ground without an in-flight data selection process.



The HelioSwarm Observatory in Relative Scale



HelioSwarm Science Goals and Objectives

Science

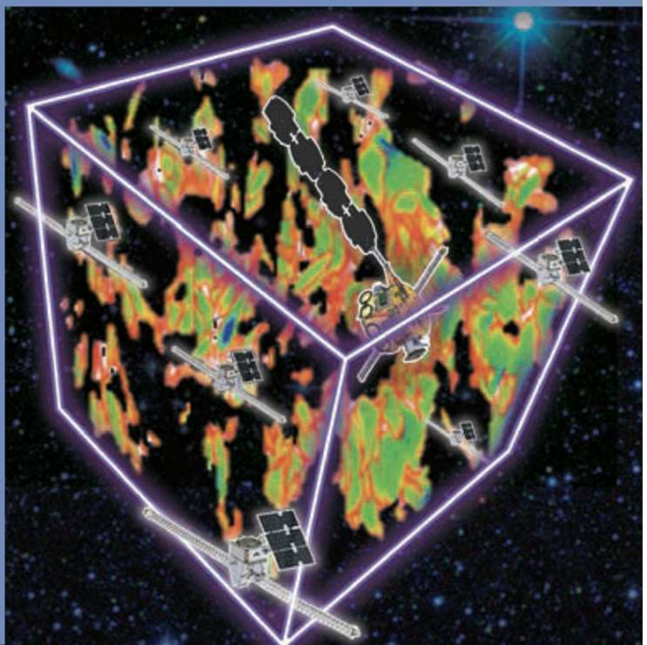
HelioSwarm science is tightly aligned with NAS 2013 Heliophysics Decadal Survey and NASA SMD Priorities: Turbulence identified as a Decadal Science Goal ("Understand the origins and effects of turbulence") and a Decadal Imperative ("Implement . . . a multispacecraft mission to address cross-scale plasma physics")

Goal #1: Reveal the 3D spatial structure and dynamics of turbulence in a weakly collisional plasma.

- O1: Reveal how turbulent energy is transferred in most probable,undisturbed solar wind plasma and distributed as a function of scale and time.
- O2: Reveal how turbulent cascade of energy varies with background magnetic field and plasma parameters in different environments.
- O3: Quantify transfer of turbulent energy between fields, flows, and protons.
- O4: Identify thermodynamic impacts of intermittent structures on proton distributions.

Goal #2: Ascertain the mutual impact of turbulence near boundaries and large-scale structures.

- O1: Determine how solar wind turbulence affects and is affected by large-scale structures.
- O2: Determine how strongly driven turbulence in the foreshock, magnetosheath, and magnetosphere differs from that in the undisturbed solar wind.



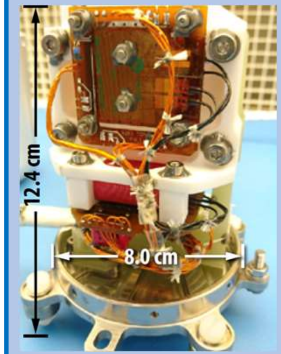
HelioSwarm's first-ever simultaneous multipoint, multiscale measurements disentangle spatial and temporal variations in solar wind plasmas that connect MHD scale turbulence with sub-ion scale heating.

HelioSwarm Instrument Suite

Hub and Nodes

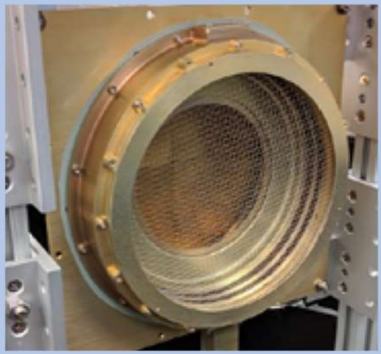
Hub only

MAG – Fluxgate (Imperial College)

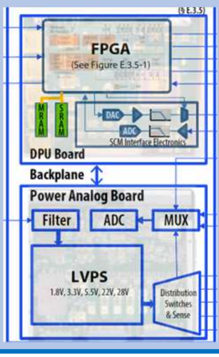


SCM – Search Coil (LPP/LPC2E)

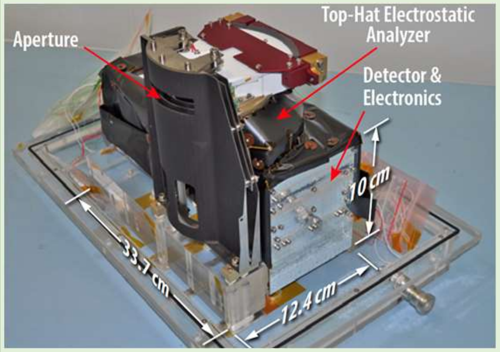
FC – Faraday Cup (SAO/Draper/UCB)



IDPU – Inst. Dig. Proc. Unit (UNH)



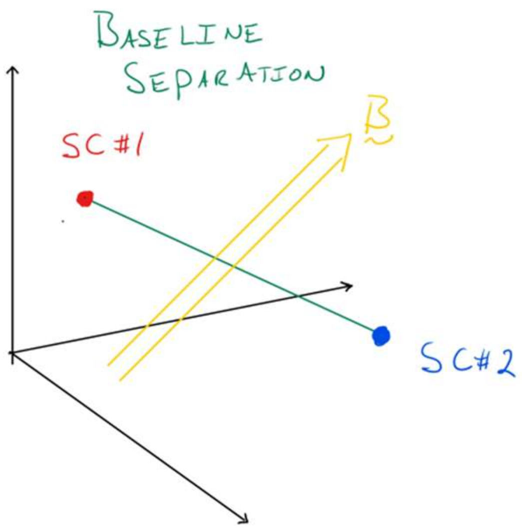
iESA – Ion Electrostatic Analyzer (IRAP/LAB/UNH/MSSL)

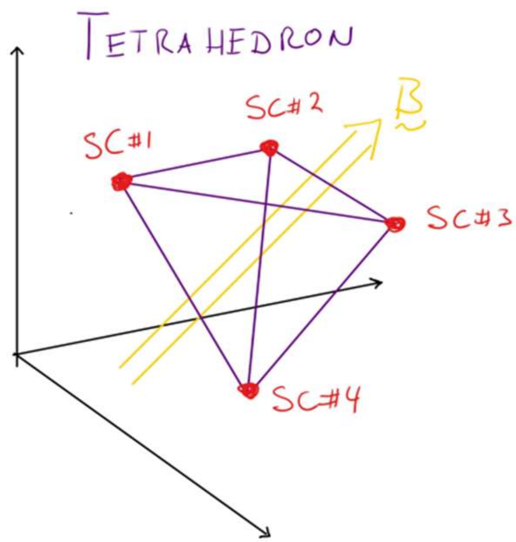


Student Electron ESA (UCB) (UCB)

MAG	SCM	FC	IDPU	iESA	Student Electron ESA
Tim Horbury (Lead)	Olivier Le Contel (Lead)	Mike Stevens (Lead)	(Lead)	Benoit Lavraud (Lead)	Phyllis Whittlesey (Lead)
Imperial College London	LPP/CNES	Smithsonian Astrophysical Observatory	University of New Hampshire	IRAP/CNRS	UC Berkeley

HelioSwarm inter-spacecraft geometries





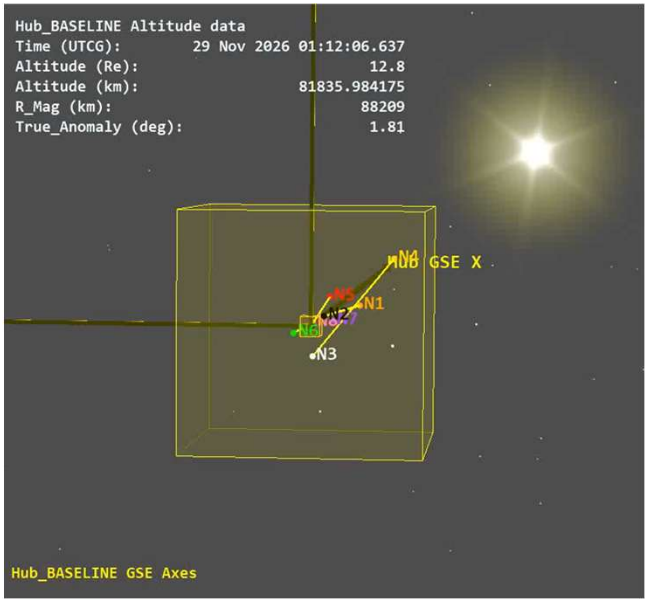
# Spacecraft	4	5	6	7	8	**9**	10	11
baselines	6	10	15	21	28	**36**	45	55
tetrahedra	1	5	15	35	70	**126**	210	330
total polyhedra	1	6	22	64	163	**382**	848	1816

- More spacecraft fundamentally yields more
  - *baselines* scaling as N(N-1)/2)
  - *polyhedral shapes [e.g.* the number of *tetrahedra scaling* as *C(N,4)=N!/(4!(N-1)!)]*

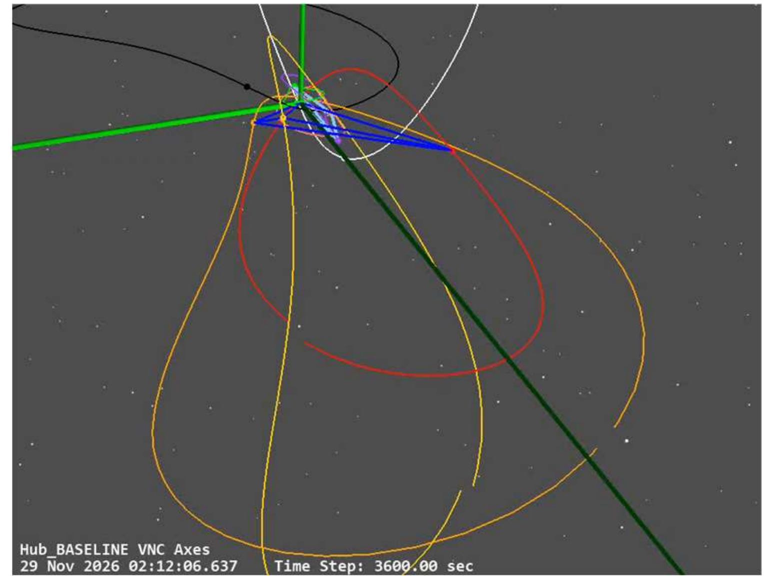
- The more baselines and polyhedra an observatory measures, the more scales can be covered, and the more data is produced for statistical analysis methods.

- The number of nodes was selected to yield a sufficient number of configurations with the appropriate shapes covering the physical scales of interest.

HelioSwarm Leverages Heritage Analysis Techniques for Studying Turbulence



Complementary Analysis Approaches characterize the fluctuations along or transverse to local field or flow directions using differences in the plasma across **baseline separations** and directly reconstruct the three-dimensional structure of the turbulent fields and flows by combining measurements from the vertices of **polyhedra.**

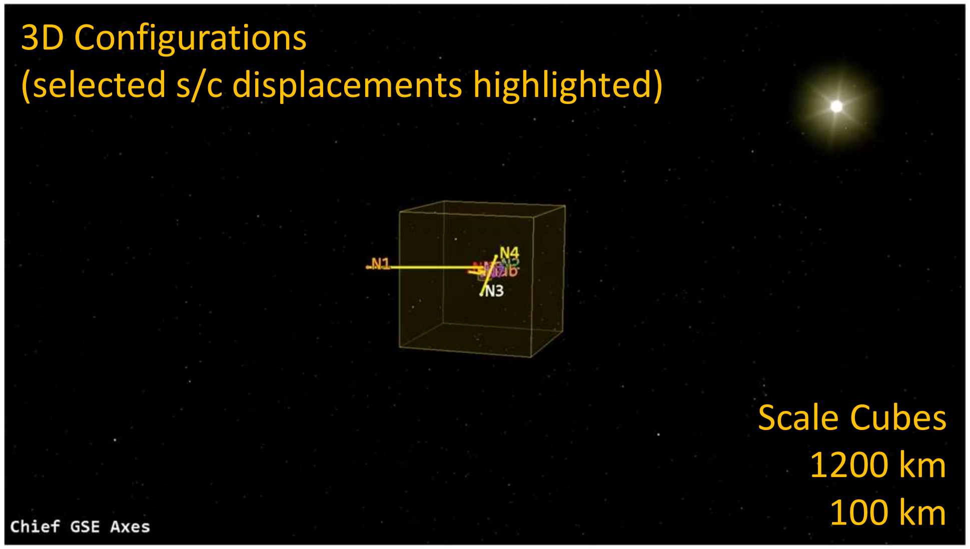


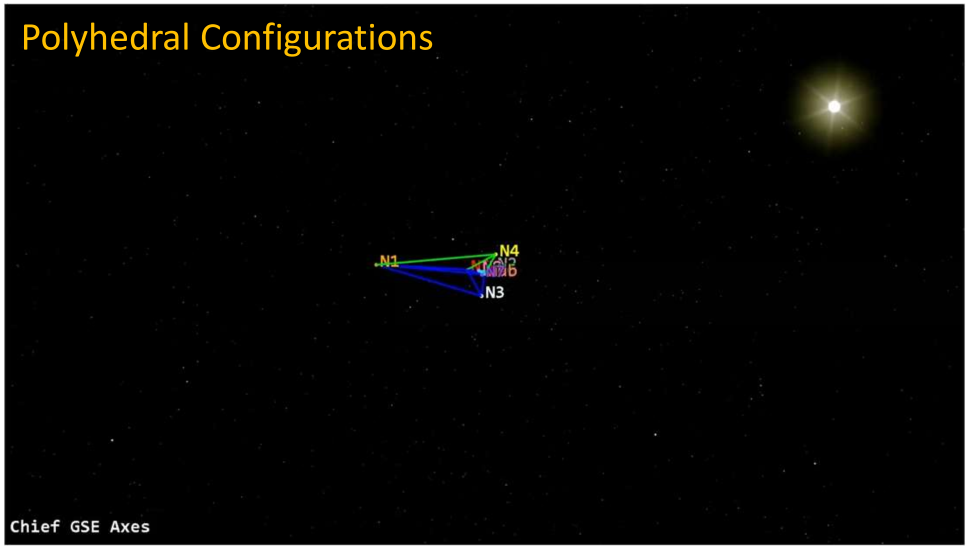
Cascade Rate: Measure of the transfer of a turbulent fluctuation energy from one spatial scale to another.
2-point correlation: Measure of the temporal and spatial scale over which a spectral element is remade by nonlinear processes.
Structure Functions: Statistics of two-point increments of turbulent fields to reveal scale-dependent, intermittent turbulence.

Wave telescope: Multipoint method for determining the wavevectors of plasma waves and their associated 3D power distributions.
Pressure-strain interaction (Pi-D): Measurement of the dilation, $-(P\cdot\nabla)\cdot v$, describing the local conversion between flow and thermal energy.
Curlometer & Gradient Methods: Multipoint methods for constructing current density/intermittent structures from spatially distributed measurements.

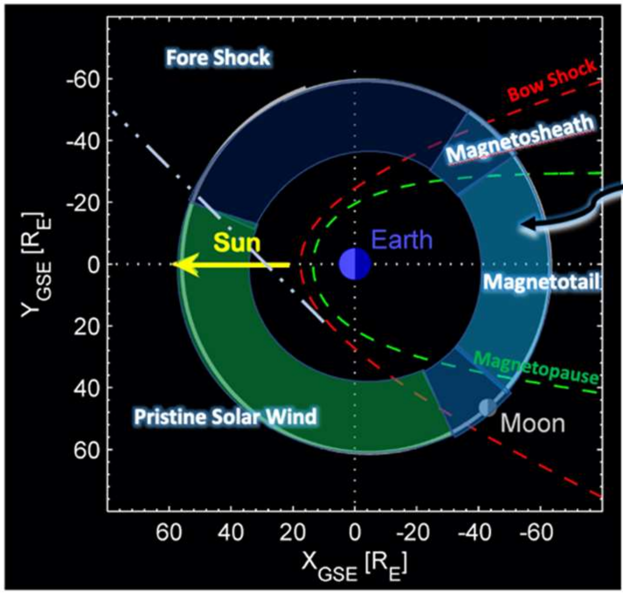
Refresher on Science Configurations

HelioSwarm's Level 1 requirements call for observations in two categories of science configurations:



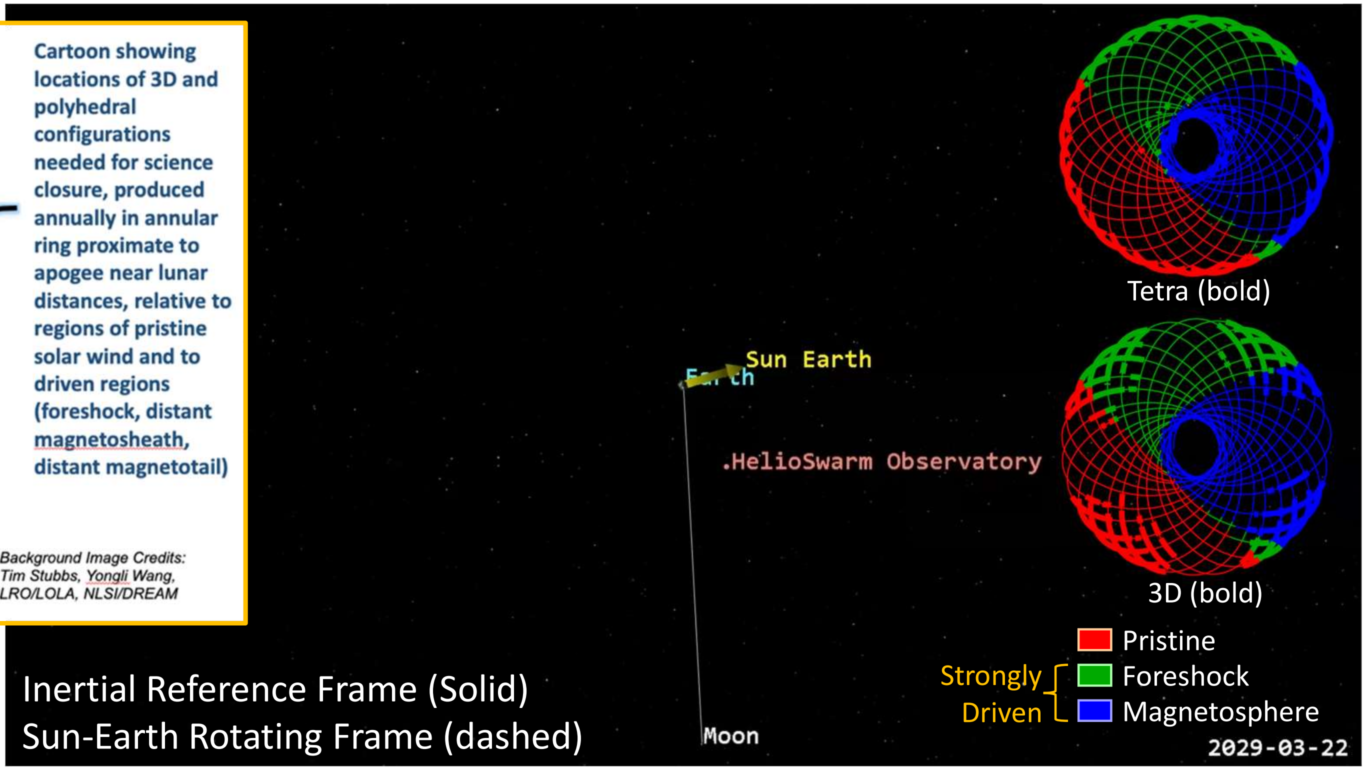


Space Plasma Turbulence Regions

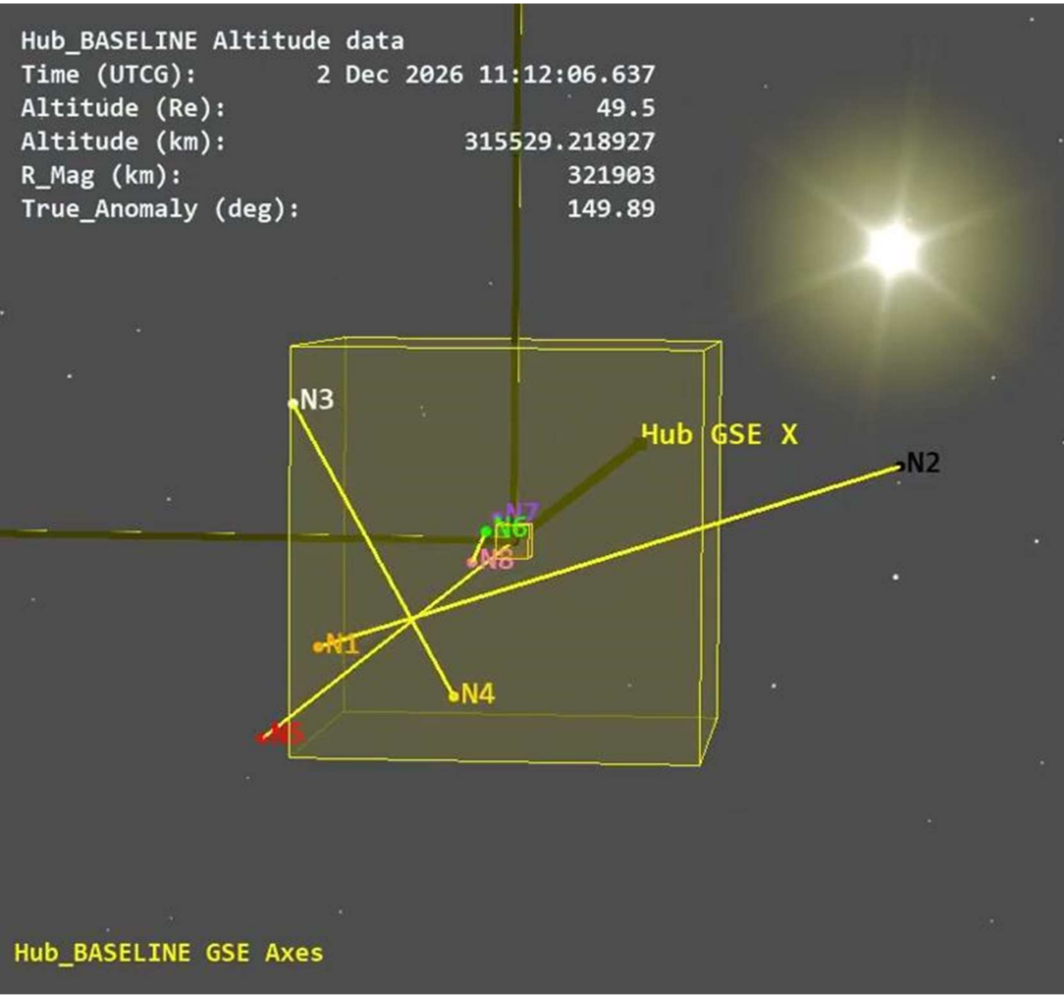


Cartoon showing locations of 3D and polyhedral configurations needed for science closure, produced annually in annular ring proximate to apogee near lunar distances, relative to regions of pristine solar wind and to driven regions (foreshock, distant magnetosheath, distant magnetotail)

Background Image Credits: Tim Stubbs, Yongli Wang, LRO/LOLA, NLSI/DREAM



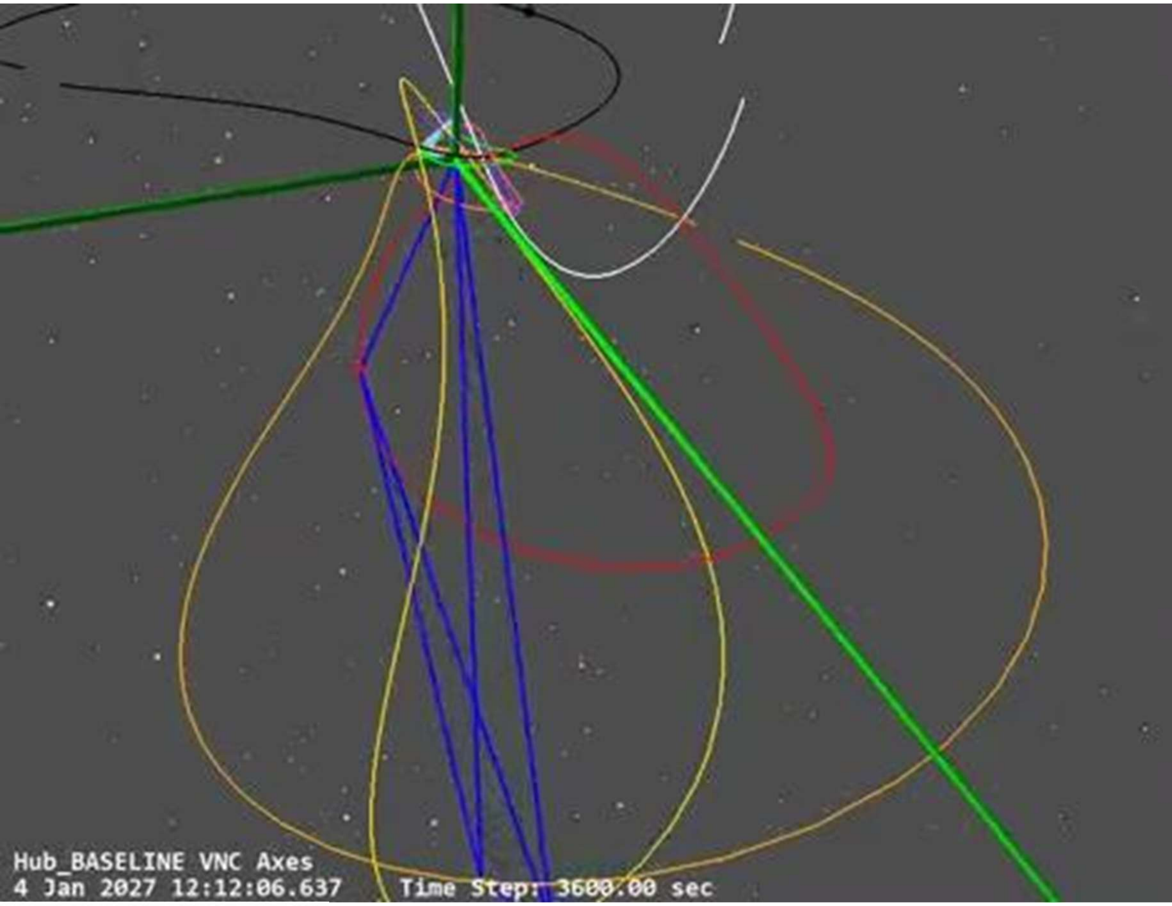
HelioSwarm's science orbit enters both the pristine solar wind and regions of strongly driven turbulence as the Earth orbits the Sun.

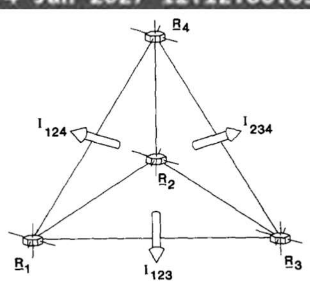


In order to study how the turbulence reshapes itself and how energy is transferred from larger to smaller scales, we need to measure the magnetic field and plasma density and velocity across **baseline separations** that are on fluid scales (>1000’s of kms) as well as on scales corresponding to the motions of the protons (<100km) simultaneously.

Cascade Rate: Measure of the transfer of a turbulent fluctuation energy from one spatial scale to another.
2-point correlation: Measure of the temporal and spatial scale over which a spectral element is remade by nonlinear processes.
Structure Functions: Statistics of two-point increments of turbulent fields to reveal scale-dependent, intermittent turbulence.

$$S_n(\lambda = \mathbf{x}_i(t+\tau) - \mathbf{x}_j(t)) =< \{\delta B[\mathbf{x}_i(t+\tau), t+\tau] - \delta B[\mathbf{x}_j(t), t]\}^n >$$





$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}$$

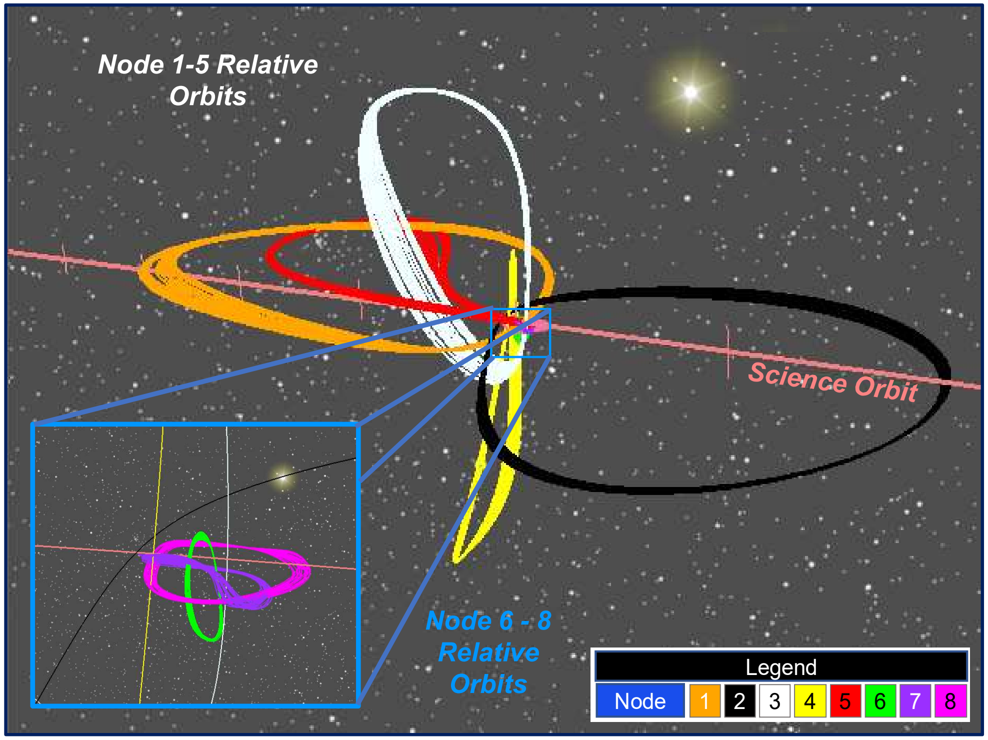
In order to measure changes in three dimensional structure and gradients requires measurements of the plasma and magnetic field made at at least four space (i.e. the vertices of a **tetrahedra** or more general **polyhedra**). The canonical example is the **curlometer** method, which enables the measurement of the current from the curl of the magnetic field.

These can be coupled with measurements of the temperature at a single point to quantify the plasma heating.

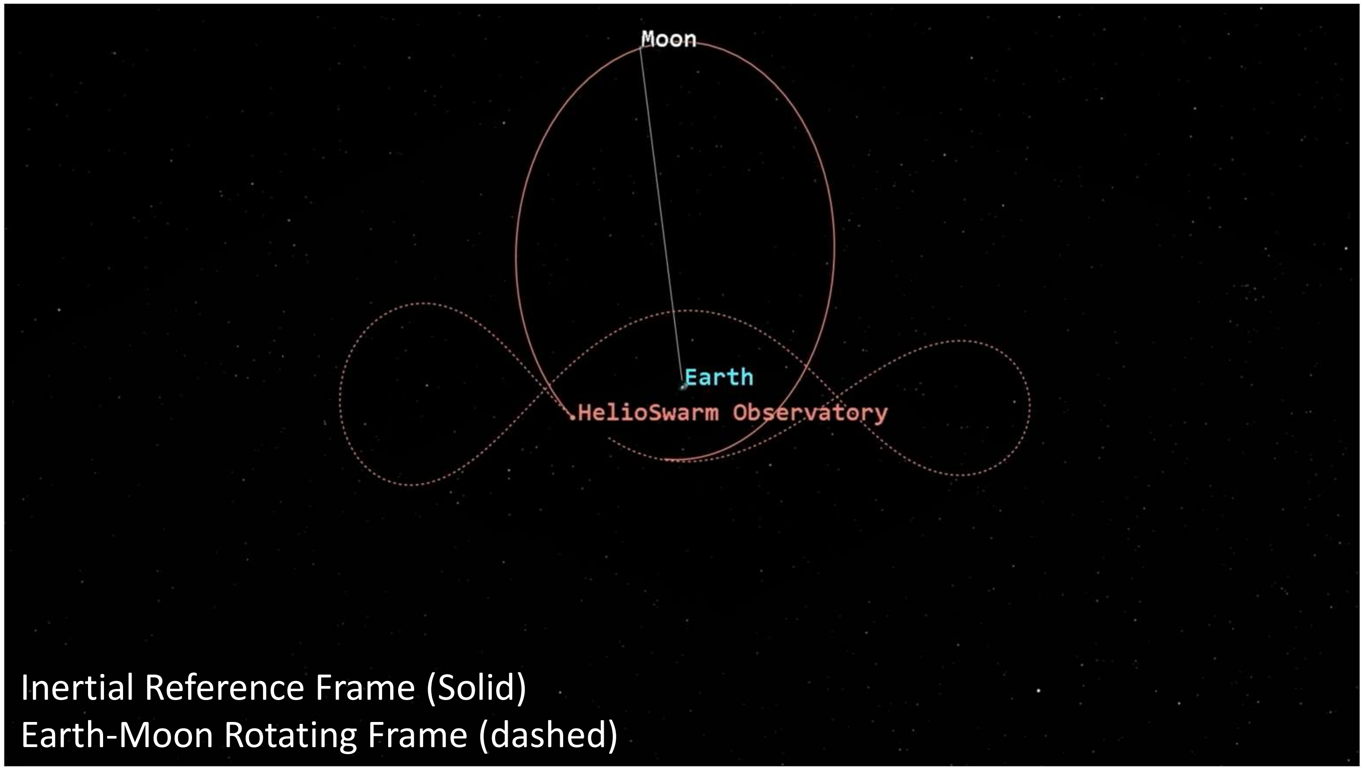
Wave telescope: Multipoint method for determining the wavevectors of plasma waves and their associated 3D power distributions.
Pressure-strain interaction (Pi-D): Measurement of the dilation, -(P·▽)·v, describing the local conversion between flow and thermal energy.
Curlometer & Gradient Methods: Multipoint methods for constructing current density/intermittent structures from spatially distributed measurements.

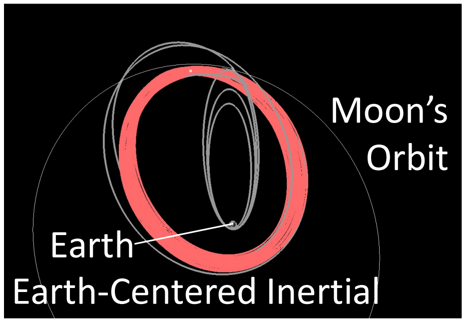
Node Relative Orbits

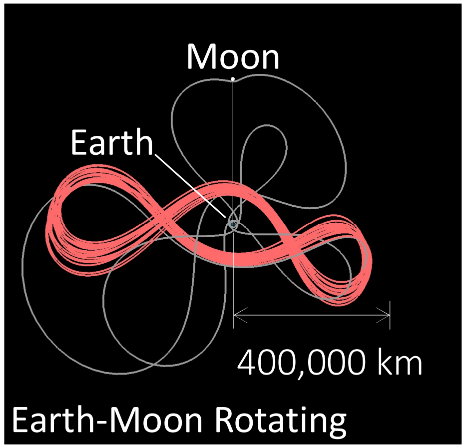
- Very small differences in each of the Node's individual High Earth Orbits result in "relative orbits" of each Node about the Hub (see diagram)
- Relative orbits are designed to meet science observation requirements
- Nodes' relative orbits keep each Node within 2000 km of the Hub at all times, with the closest approaches <200 km
- Swarm naturally expands at apogee and contracts at perigee
- ~2 orbit maintenance maneuvers per Node per orbit to maintain the relative orbits



Lunar Resonant Orbit



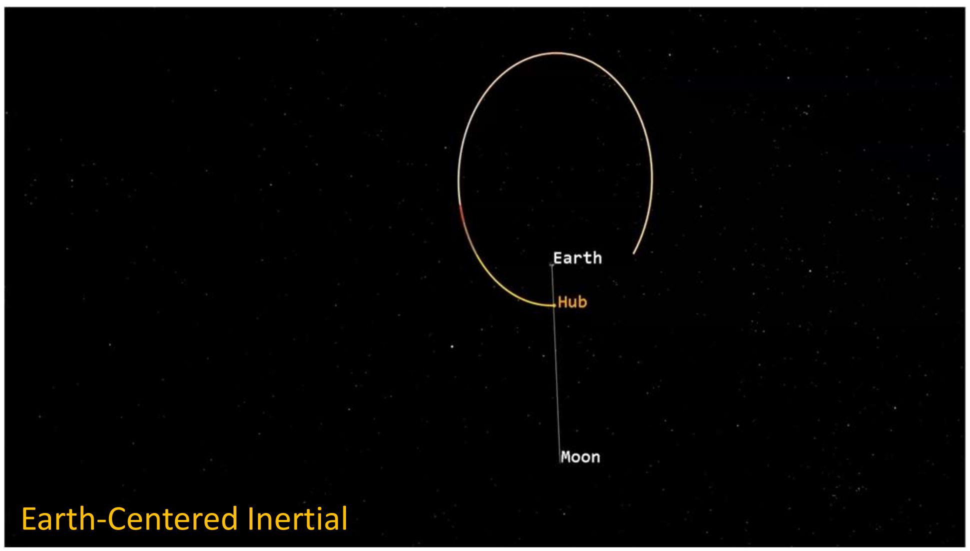


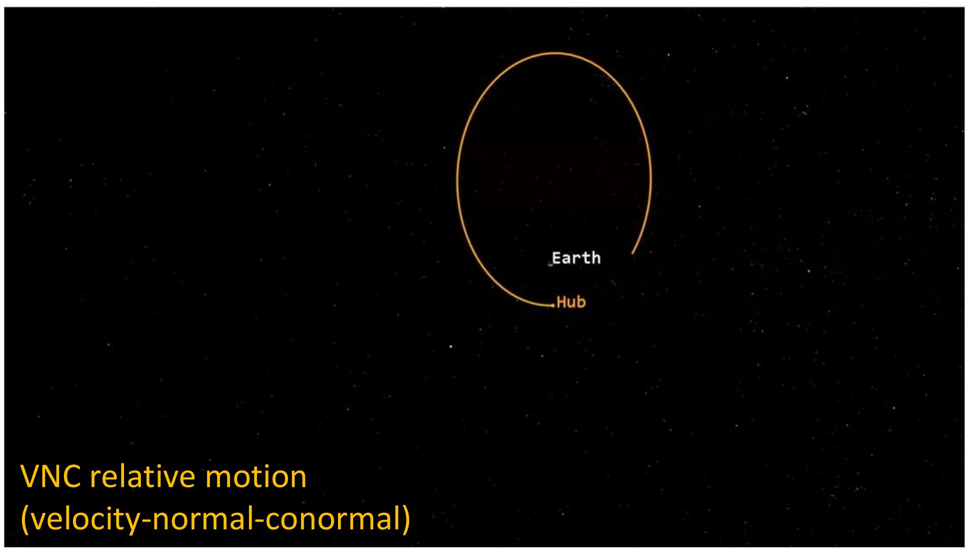


HelioSwarm's P/2 lunar resonant orbit keeps the observatory far from the Moon (similar to TESS and IBEX).

Spacecraft Relative Motion

- The Nodes do not orbit the Hub; they orbit the Earth
- Relative motion is an emergent property from tiny differences in observatory members' orbits **around the Earth**





Same motion, different reference frame

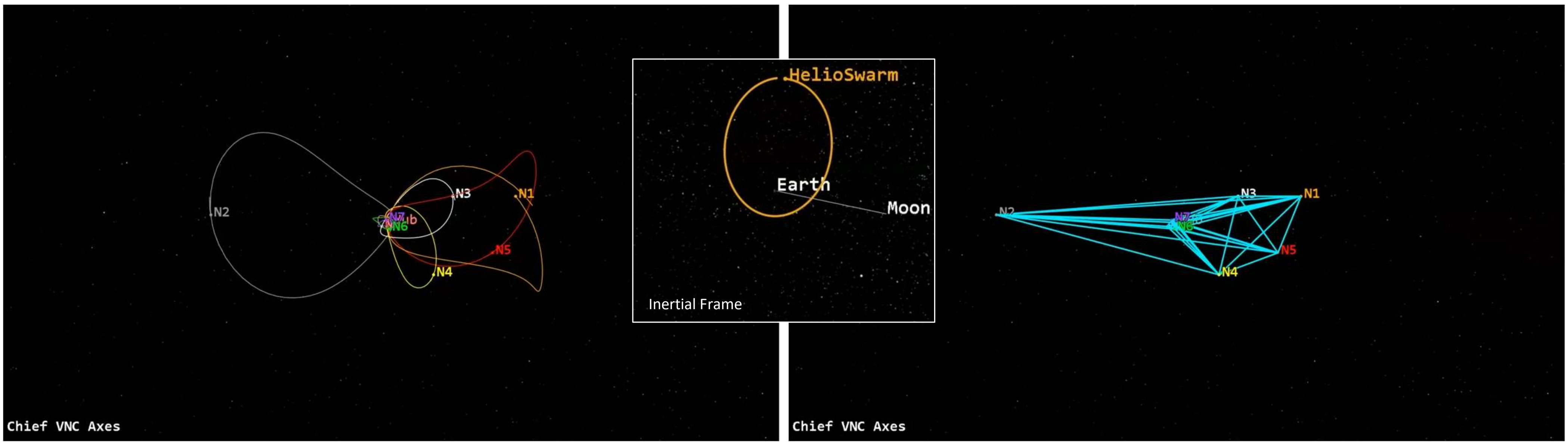
The Swarm is the Observatory

The Swarm **is**

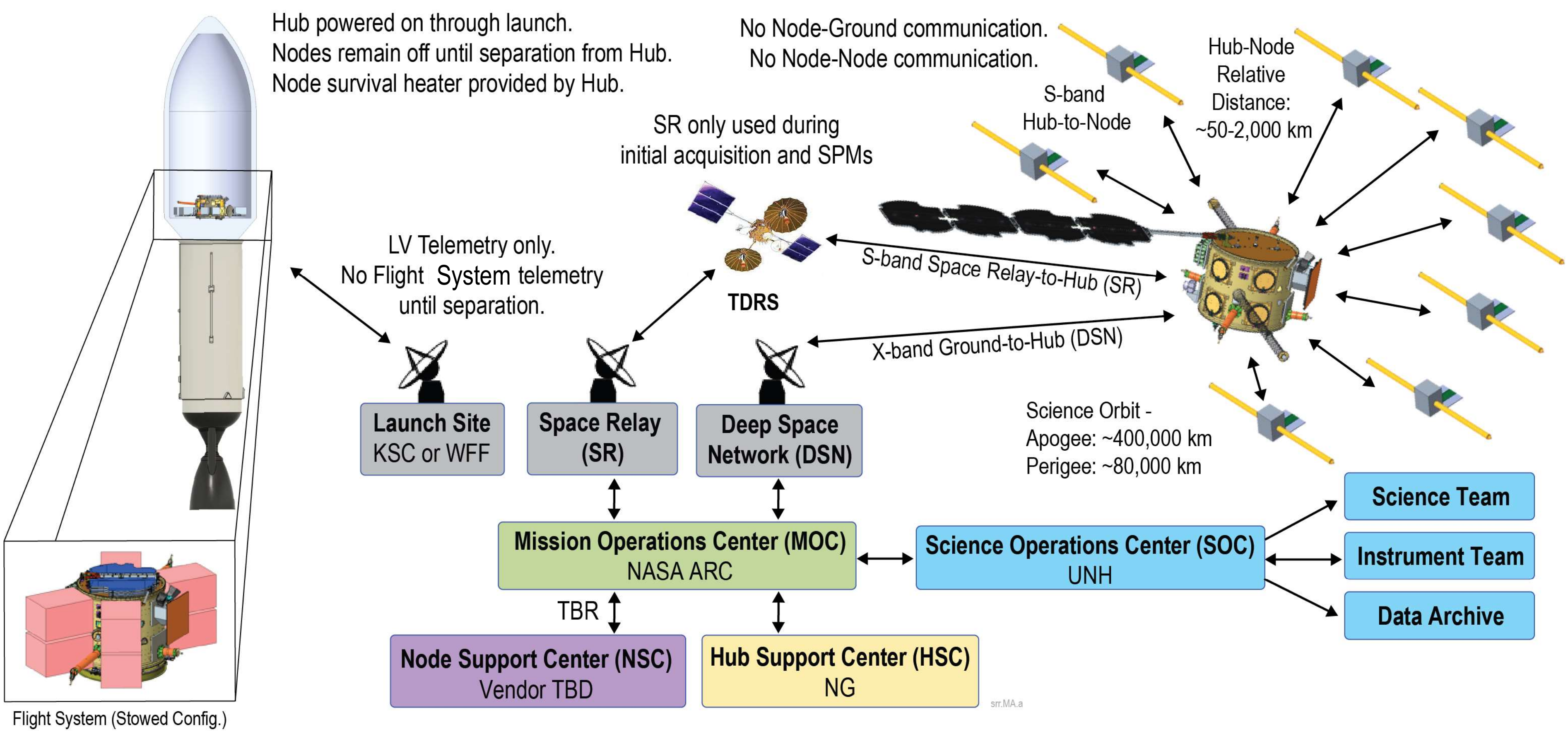
- Nine co-orbiting satellites
- Obliged to orbital motion
- Relative orbital motion is not arbitrary; rather, it results from tiny differences in the Earth-centered orbits of the swarm members

The Observatory

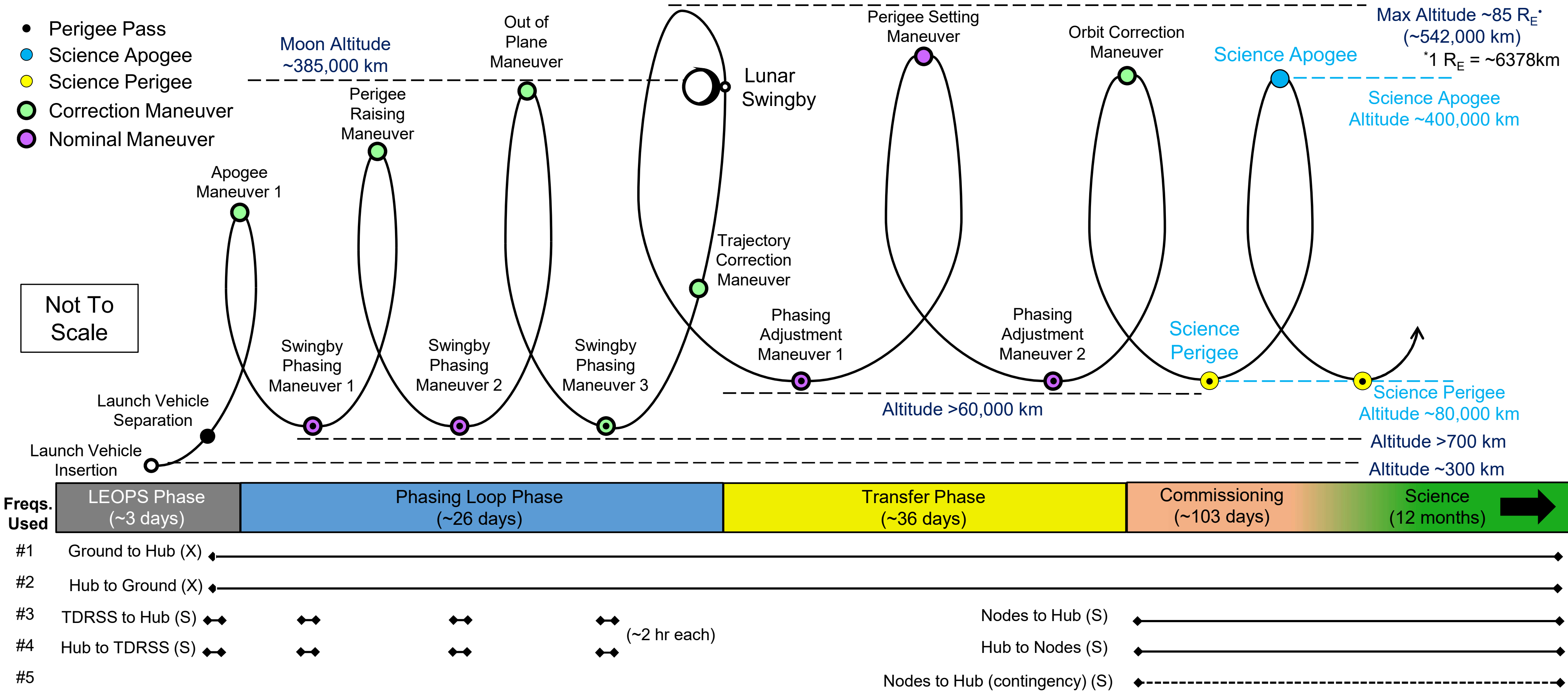
- Nine points of data collection
- Obliged to tetrahedral and 3D configuration requirements
- Successful formations occur cyclically: inter-satellite distances expand near apogee and contract near perigee



HS Mission Architecture



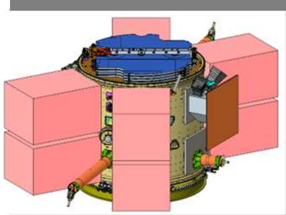
Mission Phases and Frequency Usage

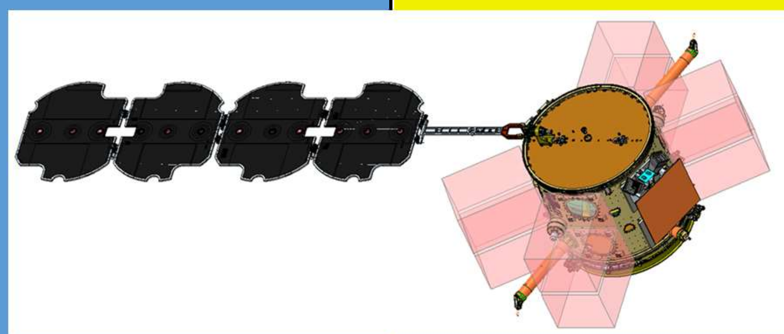


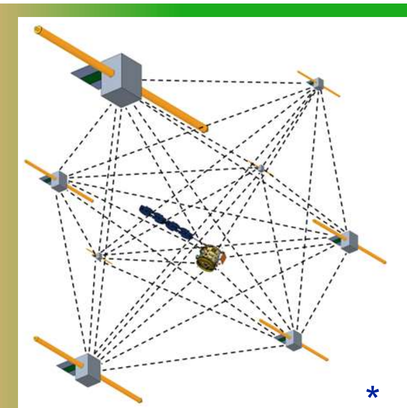
Spacecraft Configurations

HELIO SWARM

	Launch	Phasing Loop (~26 days)	Transfer (~36 days)	Commissioning (~103 days)	Science (12 months)
Space Segment Configuration	Nodes Attached to ESPA Ring	Nodes Attached to ESPA Ring	Nodes Attached to ESPA Ring	Nodes detach from Hub Establish Crosslink Nodes receive maneuver sequences, position in swarm relative orbit Power Payload IS Deploy 2 IS booms	
Mission Phases	**Launch**	**Phasing Loop (~26 days)**	**Transfer (~36 days)**	**Commissioning (~103 days)**	**Science (12 months)**





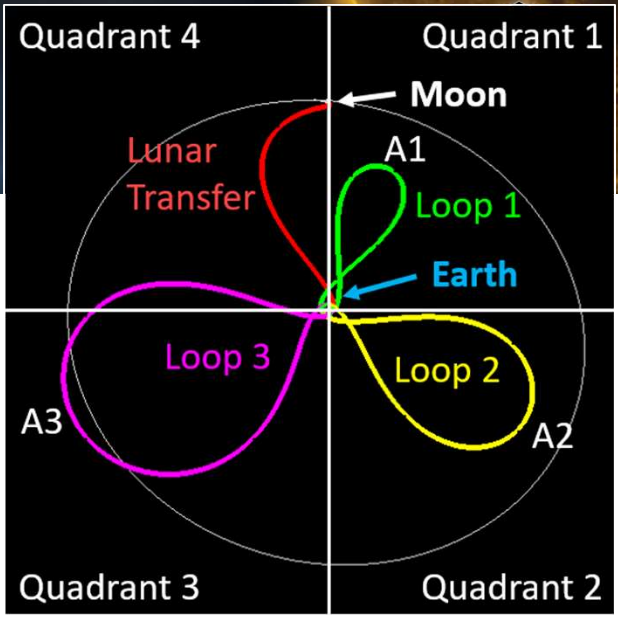


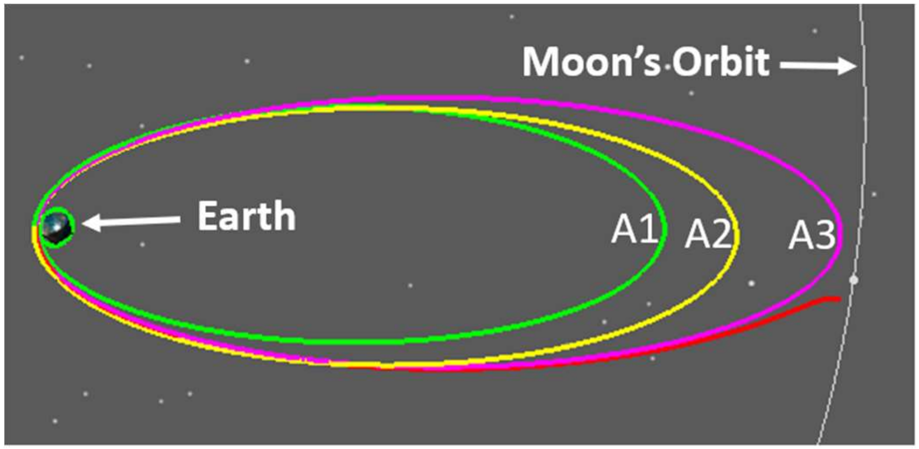
Flight System is placed into Science Orbit as one unit

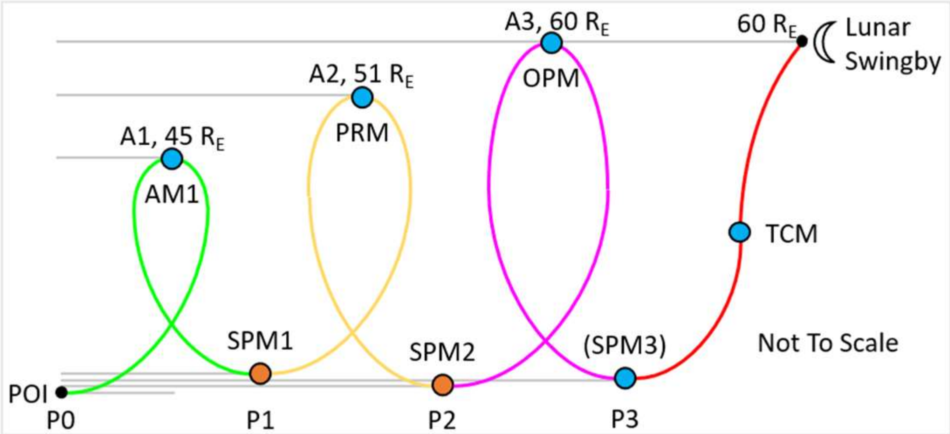
*No Node-Node communications; lines indicate S/C displacements

Design of Phasing Loops

- First loop set by launch and trails Moon in 1st quadrant
- First quadrant lunar encounter raises first perigee (perigee raising maneuver not required for nominal launch performance)
- No deterministic maneuver required at P3
- Size of 2nd and 3rd loop adjust to accommodate launch dispersions and launch delays
- Similar phasing orbit strategy used on past missions (TESS, LADEE, Clementine, Wind, WMAP)

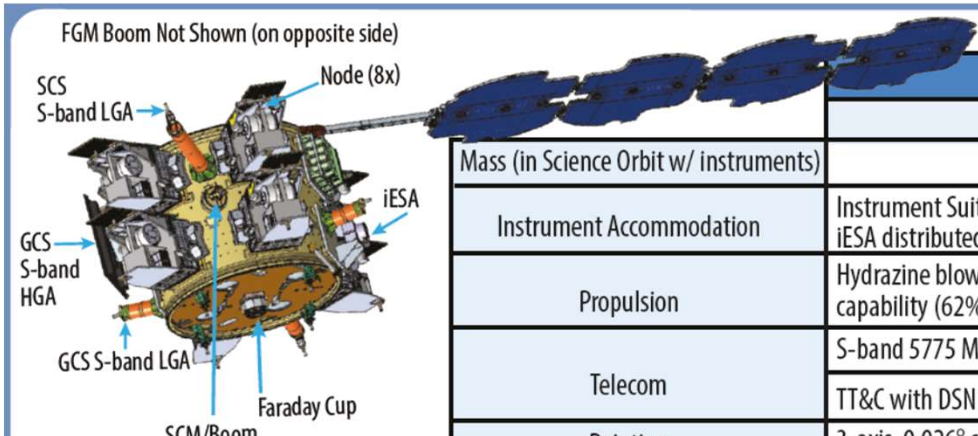






Flight System Characteristics

HELIO SWARM



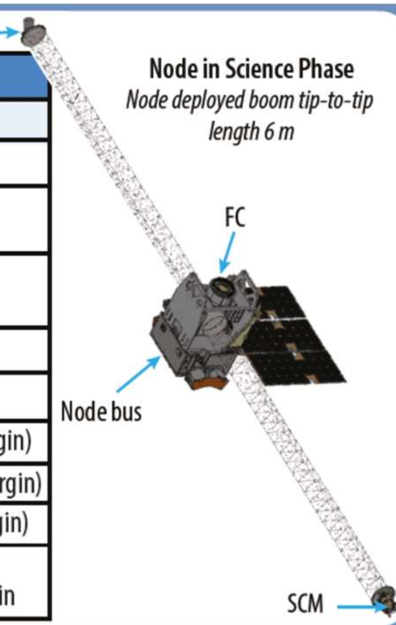
Hub with attached Nodes in Transfer Phase
Hub max dimension in Transfer 8.2 m

Total Flight System Mass: 1614 kg (96% margin in LV Scenario 3)

Key Spacecraft Characteristics

	Hub	Node (x8)
Mass (in Science Orbit w/ instruments)	727 kg	73 kg
Instrument Accommodation	Instrument Suite and iESA distributed on S/C	Single I/F to Integrated Instrument Suite & Frame
Propulsion	Hydrazine blowdown, 252 m/s capability (62% tank margin)	Solar Electric, 50 m/s capability (21% tank margin)
Telecom	S-band 5775 Mbps to DSN	S-band 250 kbps to Hub
	TT&C with DSN	TT&C with Hub (rel. ranging only)
Pointing	3-axis, 0.026° control (>1700% margin)	3-axis, 0.002° control (>600% margin)
Power	1165 W EOL single-axis SA (113% margin)	200 W EOL single-axis SA (21% margin)
	96 A-hr Li-Ion battery (30% margin)	13.2 A-hr Li-Ion battery (25% margin)
C&DH	Heritage Integrated Avionics Unit with 26 GB data, 111% storage margin	Heritage Integrated Avionics Unit with 71 GB Data, x49 storage margin

Node in Science Phase
Node deployed boom tip-to-tip length 6 m

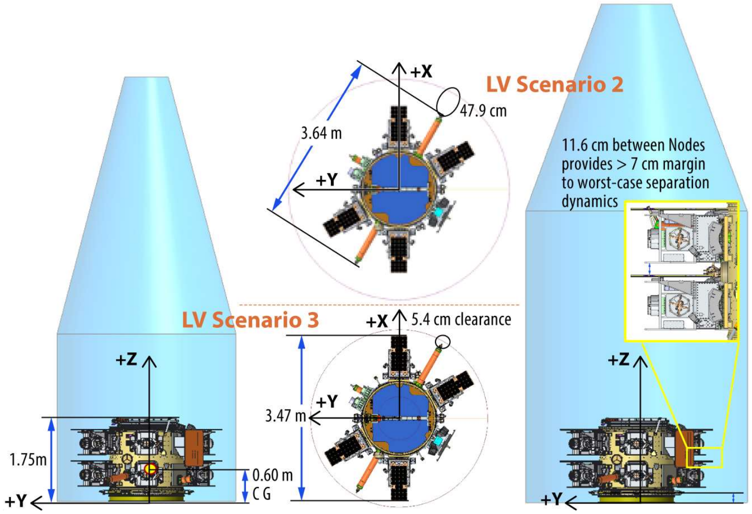


Government Reference Design

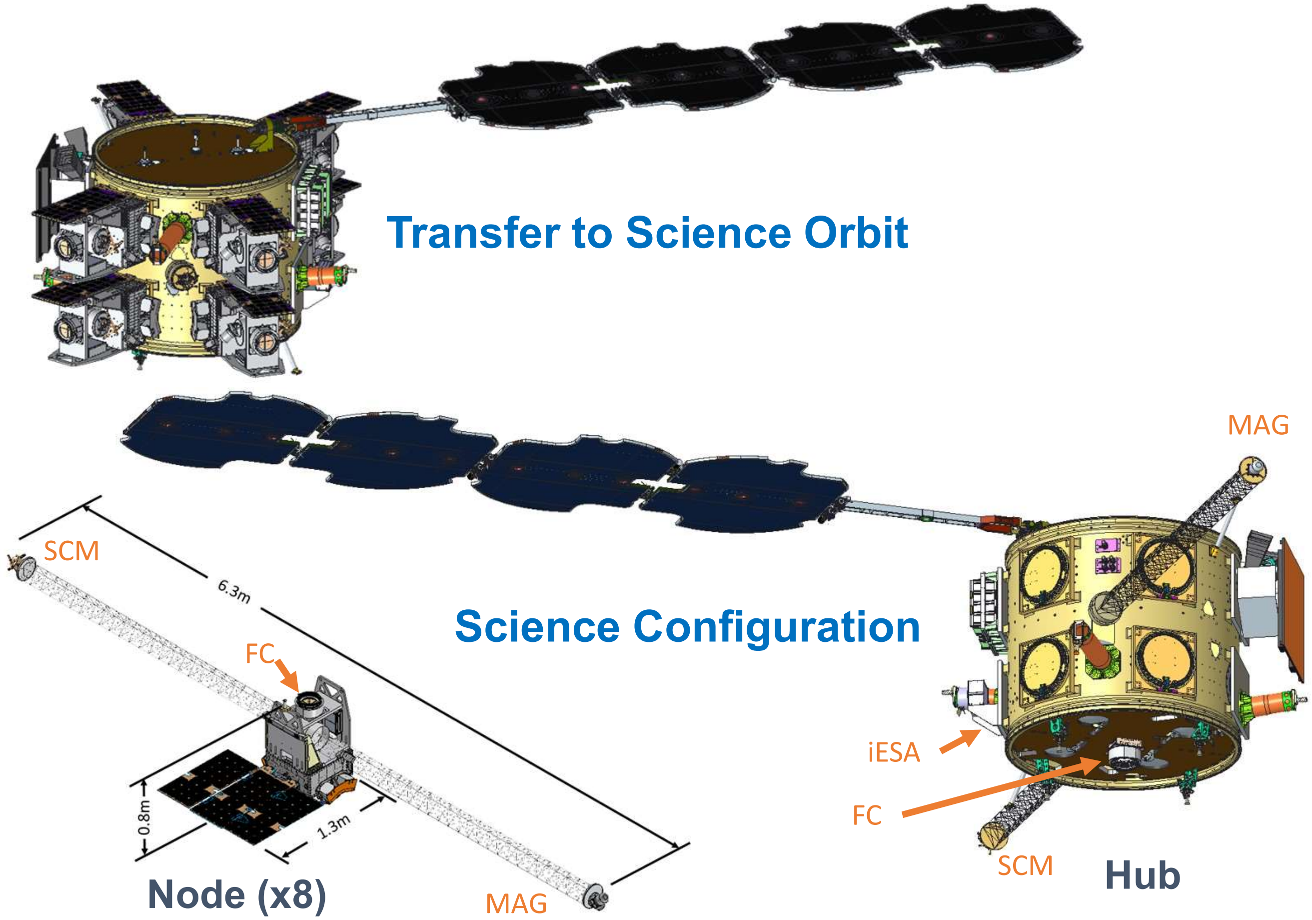
From CSR Fact Sheet; representative information but values are all outdated already!

Flight Segment

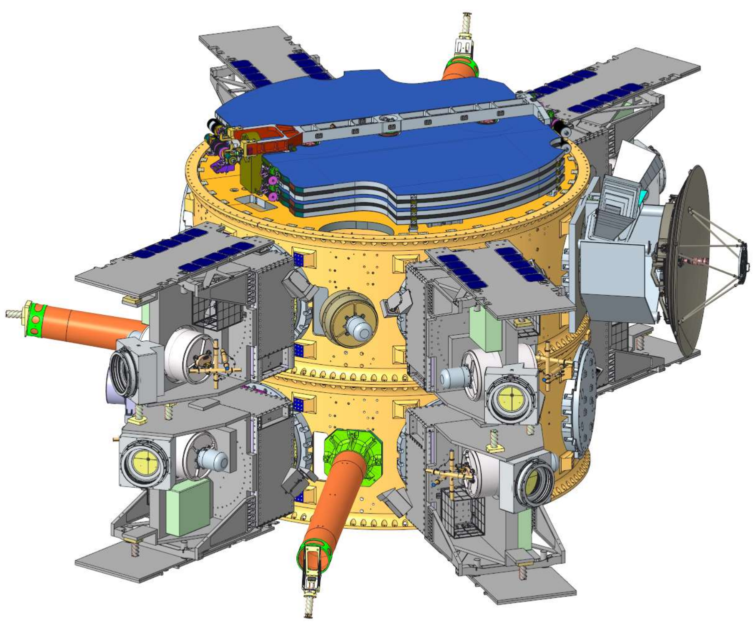
HELIO SWARM



Launch Configuration



Flight Segment



Launch Configuration

Transfer to Science Orbit

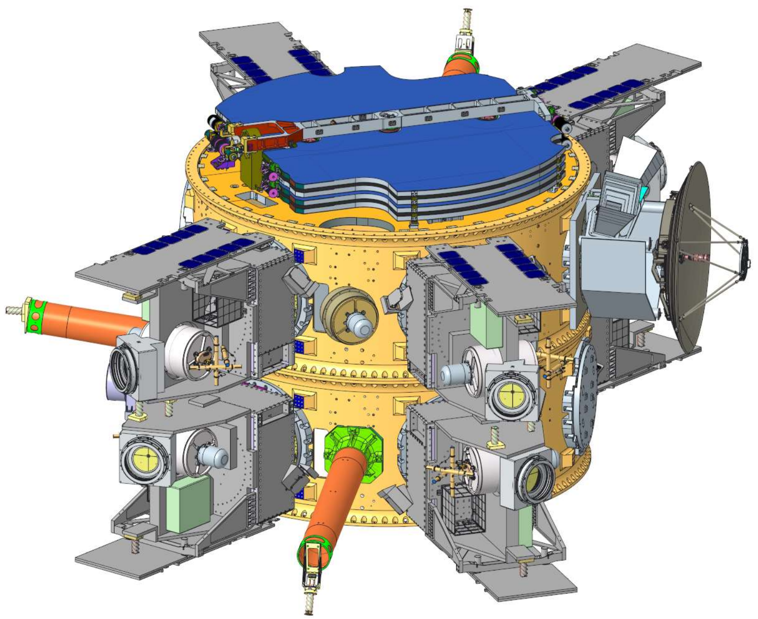
Science Configuration

Hub

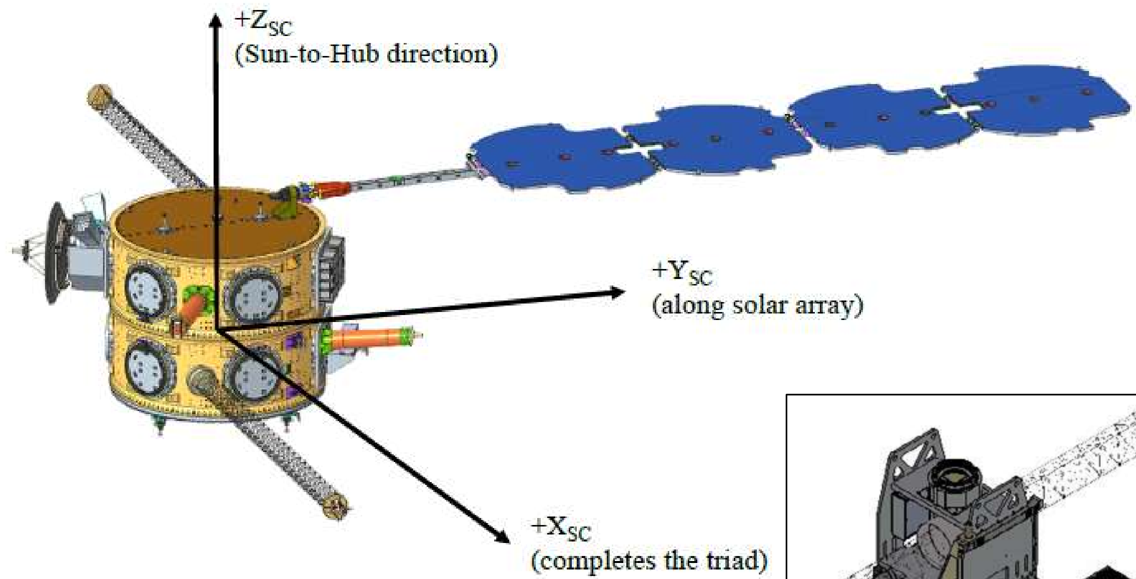
Node (x8)

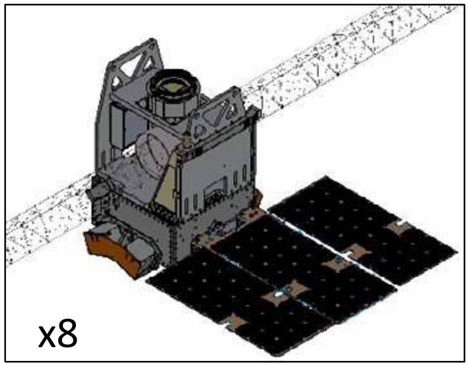
Spacecraft

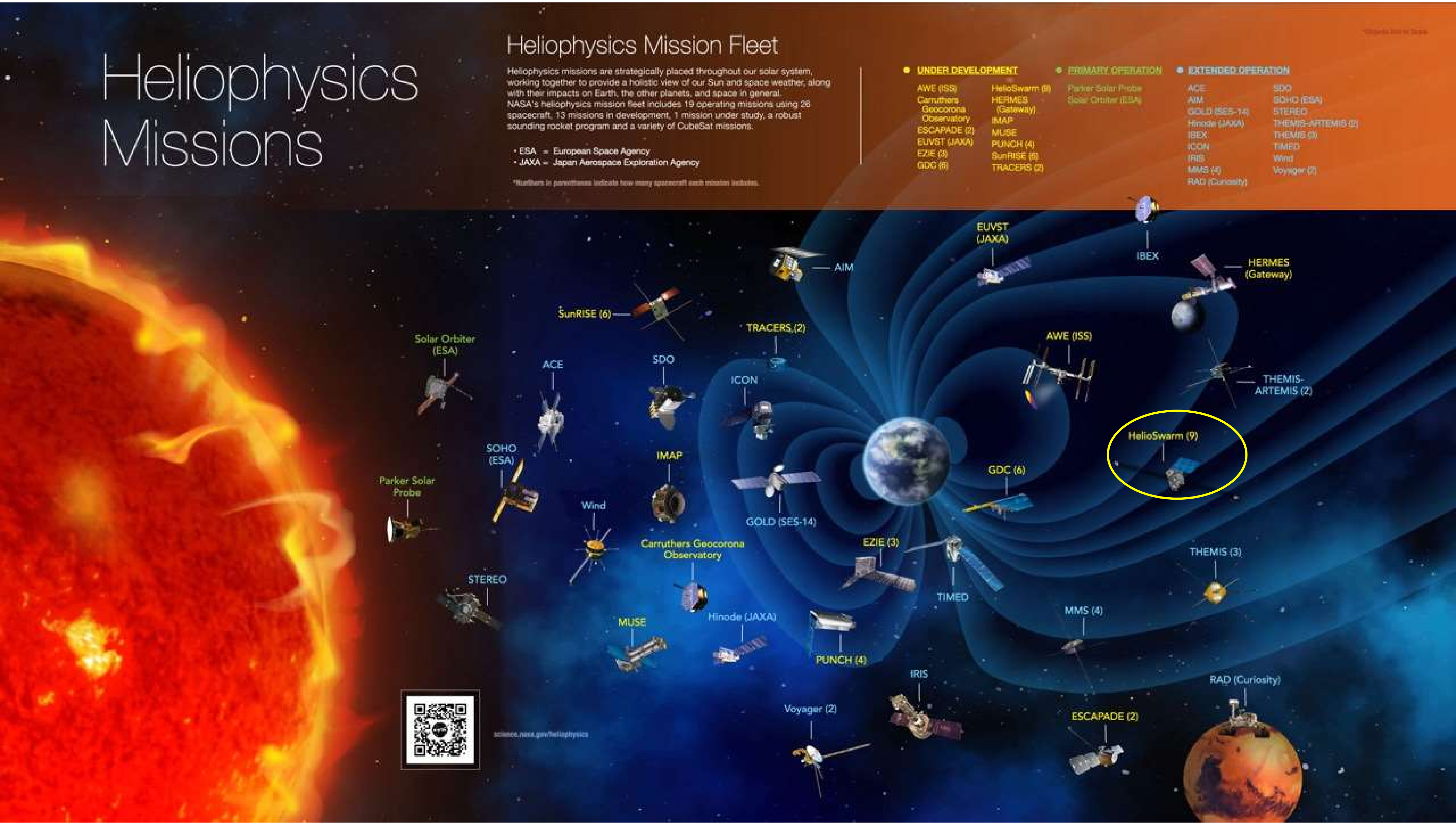
Launch Configuration (Flight System)



Science Configuration (Observatory)






Heliophysics Missions
Heliophysics Mission Fleet
Heliophysics missions are strategically placed throughout our solar system, working together to provide a holistic view of our Sun and space weather, along with their impacts on Earth, the other planets, and space in general. NASA's heliophysics mission fleet includes 19 operating missions using 26 spacecraft, 13 missions in development, 1 mission under study, a robust sounding rocket program and a variety of CubeSat missions.
• ESA = European Space Agency
• JAXA = Japan Aerospace Exploration Agency
*Numbers in parentheses indicate how many spacecraft each mission includes.
UNDER DEVELOPMENT
AWE (ISS)
Carruthers Geocorona Observatory
ESCAPADE (2)
EUVST (JAXA)
EZIE (3)
GDC (6)
HelioSwarm (9)
HERMES (Gateway)
IMAP
MUSE
PUNCH (4)
SunRISE (6)
TRACERS (2)
PRIMARY OPERATION
Parker Solar Probe
Solar Orbiter (ESA)
EXTENDED OPERATION
ACE
AIM
GOLD (SES-14)
Hinode (JAXA)
IBEX
ICON
IRIS
MMS (4)
RAD (Curiosity)
SDO
SOHO (ESA)
STEREO
THEMIS-ARTEMIS (2)
THEMIS (3)
TIMED
Wind
Voyager (2)
EUVST (JAXA)
IBEX
AIM
HERMES (Gateway)
SunRISE (6)
TRACERS (2)
AWE (ISS)
Solar Orbiter (ESA)
ACE
SDO
ICON
THEMIS-ARTEMIS (2)
HelioSwarm (9)
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GDC (6)
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STEREO
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MMS (4)
MUSE
Hinode (JAXA)
PUNCH (4)
IRIS
RAD (Curiosity)
Voyager (2)
ESCAPADE (2)
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