SSC23-II-03

HelioSwarm: The Swarm is the Observatory

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ABSTRACT

The HelioSwarm Mission will transform our understanding of space plasma turbulence by being the first-of-its-kind simultaneous, multiscale observatory comprising multiple spacecraft. HelioSwarm was competitively selected under the Heliophysics Explorers Program 2019 Medium-Class Explorer (MIDEX) Announcement of Opportunity. The central powered-ESPA Hub spacecraft is co-orbited by eight SmallSat Node spacecraft, together moving through a High Earth Orbit to obtain data in various solar wind regimes. The mission architecture is that of hub-and-spoke, with the larger hub serving as a communications relay between the Nodes and DSN. Mission operations, management, and technical oversight are provided by NASA Ames Research Center; the spacecraft are provided by Northrop Grumman and BCT. The instrument suite includes foreign-contributed and US payloads, all under the oversight of University of New Hampshire (which is also the Principal Investigator's home institution and Science Operations Center). The mission timeline from launch through conclusion of the one-year science phase is provided along with a summarized concept of operations, with particular emphasis on placing the Nodes in their proper relative orbit loops to form the geometry needed for science collection at apogee. A combination of legacy tools and custom-created swarm analysis tools are used to design the swarm and sort and visualize the collected science data and telemetry in context. Finally, an exploration of the pathfinding nature of HelioSwarm and some implications for future large scientific swarms is offered.

INTRODUCTION

Turbulence is multiscale disorder. In the solar wind, it is the process by which energy that has been injected into a system is transported between fluctuating magnetic fields and plasma motion with larger and smaller spatial scales. Once this cascade of energy reaches sufficiently small scales, dissipation mechanisms can act efficiently to remove energy from the fluctuations, leading to heating of the constituent particles. Observations from single spacecraft provide only information along a single path through a turbulent system; leveraging such measurements to understand turbulence requires relying on assumptions about the underlying spatial and temporal structure. Missions with four spacecraft, like MMS and Cluster, provide more information about spatial structure but are sensitive to only a single scale for a given configuration. Understanding fundamental processes such as turbulence requires characterizing the underlying fluctuations and their dynamic evolution across many characteristic scales simultaneously. HelioSwarm (HS) is a Medium-Class Explorer mission, under NASA's Heliophysics Division, designed to make *simultaneous temporal and multiscale observations*.

HelioSwarm has two overall science goals:

1. Reveal the 3D spatial structure and dynamics of turbulence in a weakly collisional plasma.
2. Ascertain the mutual impacts of turbulence, variability, and boundaries near large scale structures.

Klein and Spence, et al. (2023) discusses the science goals and approach in much greater detail.[1]

UNIQUENESS

The HelioSwarm mission has several novel or unique aspects to it. The observatory consists of a central larger spacecraft (the Hub) and 8 smaller spacecraft (the Nodes). The Nodes are attached to the Hub for launch and carried into the final science orbit, and then released in pairs on a two-week cadence. All of the spacecraft carry a suite of science instruments, including the Hub, making up an observatory of 9 spacecraft. The HelioSwarm mission concept leverages the capabilities of the large spacecraft for large delta-v maneuvers during transfer, high volume data return over long distances, and to perform space-based ranging on the Nodes. The complementary functions of the smaller Nodes take advantage of SmallSat features to become free-flying

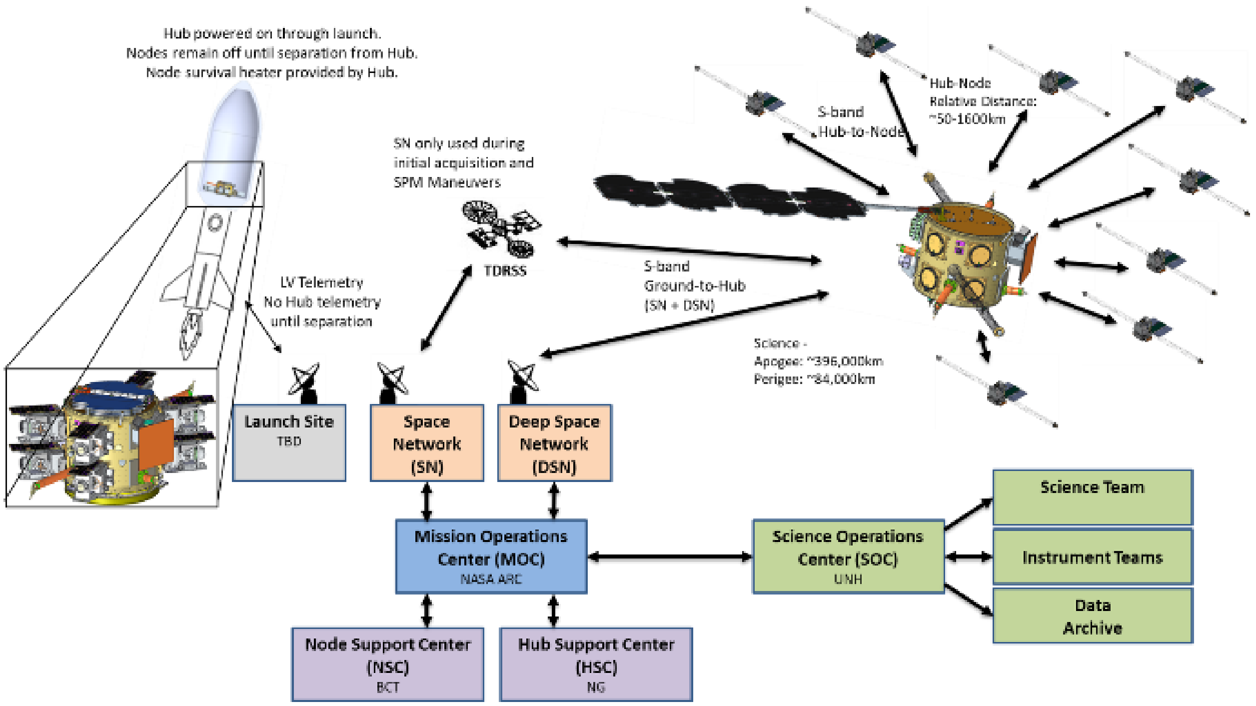


Figure 1: HelioSwarm Mission Architecture

instrument suites that need only small delta-v maneuvers and transmit data over comparatively short distances. Thirdly, the mission relies on the strengths of ground resources for tracking, operations, and maneuver planning. The Hub then communicates commands and coordinates time with each Node. The swarm is thus treated like a single object rather than several individual spacecraft.

ARCHITECTURE

To accomplish the HS goals and objectives, the observatory (consisting of 9 spacecraft) captures measurements of the solar wind proton density, velocity, and interplanetary magnetic field at multiple points in space simultaneously (the Hub plus all Nodes), as well as the proton temperature, temperature anisotropies, and alpha density at a single location (the Hub).

Three mission segments (Fig 1) work in conjunction to achieve those measurements:

- The Flight Segment consists of a single Hub spacecraft that carries and separates eight smaller Node spacecraft. All nine spacecraft carry an identical set of three science instruments on-board, with the Hub carrying a fourth instrument (plus a student collaboration instrument as well). Operated as a swarm, the Nodes communicate with the Hub, which in turn communicates with the ground using a hub-and-spoke topology. The orbits of all nine spacecraft are coordinated relative to each other to ensure the 36 baselines (separation between any two spacecraft) capture the necessary multi-scale measurements.

- The Launch Segment is responsible for the launch vehicle, launch site processing, and all corresponding support services.

- The Ground Segment includes the ground communications network, ground data systems, mission and science operations systems, and all necessary operations personnel.

PROGRAMMATICS

HelioSwarm is a NASA Medium Explorer (MIDEX) mission under the Heliophysics Division of the Science Mission Directorate (SMD), and reports to the Explorers Program Office at NASA GSFC.[2] As is normal for NASA MIDEX missions, HS is a PI-led mission, meaning that Prof. Harlan Spence, at the University of New Hampshire, is responsible for all aspects of the project and for mission success.

HS has been designated a Category II/Class C mission, which imposes mission assurance requirements on the implementation. One of the challenges for HS is meeting the rigorous mission assurance requirements using commercial-off-the-shelf Node spacecraft. HS is using redundancy and resilience at the observatory level in order to satisfy the Class C reliability requirements.

MISSION IMPLEMENTATION

Instrument Suite

All 9 spacecraft host an instrument suite (IS) science payload consisting of three scientific instruments: a Fluxgate Magnetometer (MAG), a Search Coil Magnetometer (SCM), and a Faraday Cup (FC). The three instruments are controlled by an instrument data processing unit (IDPU). Fig 2 shows the various instruments. The two magnetometers are deployed on a pair of booms, which are released from a stowed configuration once the spacecraft reach their science orbits. The Hub hosts the same IS payload as the Nodes, but also hosts an ion Electrostatic Analyzer (iESA). The measurements from all these instruments reference a time synchronization broadcast by the Hub.

Together, the MAG and SCM have the dynamic range, accuracy, and cadence needed to resolve the vector interplanetary magnetic field (IMF) from magnetohydrodynamic (MHD) to sub-ion scale frequencies. The FC measures the radial component of the proton Velocity Distribution Function (VDF) to produce density and velocity data products with a dynamic range encompassing 99+% of Solar Wind (SW) speeds, an accuracy to resolve SW variations, and a cadence to measure from MHD to sub-ion scales. The iESA measures 3D proton and alpha VDFs, enabling the alpha-proton density ratio, proton temperature, and proton temperature anisotropy data products required to characterize SW plasma; this measurement is only needed at a single point (the Hub).

Hub Spacecraft

The Hub bus is an adaptation of Northrop Grumman's evolved expendable launch vehicle (EELV) secondary pay-load adapter (ESPAStar) product line, which is designed to carry separable payloads to orbit. The Hub primary structure is an ESPA ring with aluminum honeycomb forward and aft decks, and a central bulkhead stiffener. The ESPA ring supports two rows of six payload attachment ports each with over 180 kg capability, through EELV Standard Interface Specification (SIS) environments. Aluminum adapters at eight of the ports provide mounts for Motorized Light Bands (MLBs) interfacing to each of the eight Nodes. These MLBs provide low shock, low tip-off, controlled separation of the Nodes into the science orbit. The central bulkhead provides the supporting interface for mounting the propulsion tanks and components. As an ESPA-based spacecraft, the Hub interfaces to the launch vehicle via a RUAG separation system on its -Z side. This preserves the capability of stacking atop another ESPA ring carrying secondary payloads. The solar array (SA) folds tightly onto the +Z deck, into a volume that on other ESPAStar missions is designed to allow for a second separation system, making possible a large secondary payload stacked on the +Z side. The SA mounts to the bus via a metallic yoke and deploys in a two-step process using non-explosive actuators after separation from the launch vehicle. Once deployed the SA wing rotates around a single Y-axis for sun pointing. Power is stored in a Li-Ion battery system, and the size is driven by the requirements of the Transfer Phase, when in addition to Hub bus subsystems the electrical system powers survival heaters for the attached Nodes. The Hub bus is power-positive through all mission phases. The Hub propulsion subsystem has two roles: carry out all maneuvers required to achieve the science orbit with attached Nodes and perform momentum unloads (MU) throughout the mission. Propellant is stored in four propellant tanks with integrated expulsion diaphragm to minimize slosh during maneuvers and slews. Four large thrusters are used for ΔV maneuvers during transit to the science orbit, as well as X/Y attitude control during burns using off-pulsing. Four reaction control system thrusters operating in pulse mode are used for Z-attitude control during ΔV burns, as well as for MU throughout the mission. The Hub bus Attitude Control Subsystem (ACS) is a 3-axis stabilized system to maintain attitude stability and control throughout all mission phases. The ACS is designed to control the Hub attitude for the transit to the science orbit, including during ΔV burns and Node separations, point the science

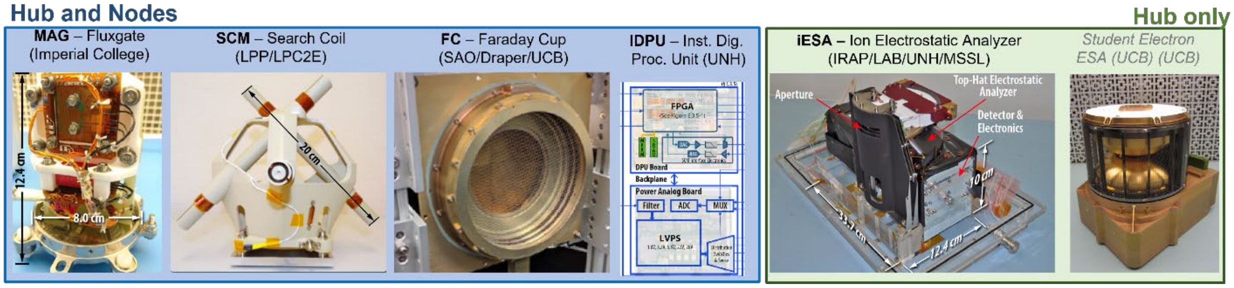


Figure 2: HelioSwarm Science Instruments

instruments at the Sun in science mode, and to point the High Gain Antenna (HGA) at the Earth during high-rate downlinks. The system also supports calibration slews for the instruments, when needed. Since the ground only communicates directly with the Hub, the Hub employs two separate communications systems. The Ground Communications Subsystem (GCS) supports TT&C links throughout the transfer and science orbits, as well as high-rate data downlinks near perigee, both through a single 34-m DSN antenna; and to be compatible with Space Network (SN) TT&C in early mission. The GCS uses an S-band transponder with two hemispherical low-gain antennas (LGAs), and a HGA connected via rotary switches on the transmit path. When switched to the LGAs, the transmitter side of the transponder is primarily used to downlink Observatory housekeeping (HK) telemetry (TLM), as well as stored Hub-Node relative ranging data. The GCS switches to the HGA to transmit stored science data during perigee passes. In both stowed and deployed configurations, the combined LGAs provide near 4π-str coverage for both uplink and downlink. The Space Communications Subsystem (SCS) is separate from the GCS and provides communications between the Hub and all of the Nodes. The SCS is also used to provide time-of-flight (TOF) relative ranging measurements between the Hub and Nodes. The science data sent from the Nodes to Hub are stored on-board the Hub until scheduled for download at the perigee passes. The on-board storage in the Hub is sufficient for multiple missed perigee passes without losing any science data.

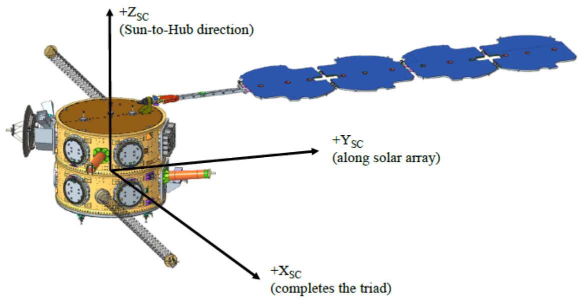


Figure 3: The HelioSwarm Hub in the deployed science configuration.

Node Spacecraft

The HS Node bus uses Blue Canyon Technologies' (BCT's) Venus bus SmallSat platform. The Venus bus platform is specifically designed to accommodate a range of payloads and flight envelopes, and was chosen as a Commercial-Off-The-Shelf (COTS) for the HS mission. The mechanical, propulsion, power, ACS, and C&DH from the Venus bus meet HS needs with no modification, besides mission-specific SW which is at >90% reuse. This is an important aspect of the mission, since a custom spacecraft design for the Nodes would not be affordable within the HS cost-cap. The Venus bus structure consists of two honeycomb aluminum panels as the top and bottom decks with aluminum machined side panels. The bottom honeycomb deck has an integrated bolt pattern to allow for the integration and use of a MLB to match the ESPA ports on the Hub. The top honeycomb deck has three unique bolting patterns to better accommodate the integration of any payload onto the Venus bus. For the HS mission, the IS uses a standard bolt pattern that runs around the perimeter of the top deck. Two thruster modules comprised of two thrusters each are mounted externally on both sides of the bus box. The Node bus propulsion system has two roles: carry out all maneuvers required to achieve the science orbit for each individual Node and manage momentum build up. The SA stows tightly along the side of the bus box with support structures that protrude from the top deck around the IS. The SA is mounted to the bus via an aluminum yoke and deploys in a two-step process. Frangibolt actuators restrain and deploy the SA without releasing contamination/debris. The Node is 3-axis controlled with an ACS. The Node ACS is designed to control Node attitude during all phases and modes of the HS mission, including Sun-safe, thrusting maneuvers and Sun point science mode. Prior to separation from the Hub, all Node ACS components are powered off. Upon separation, the Nodes boot into Sun-safe mode using only Sun sensors, IMU, and reaction wheels to point the SA at the Sun and rotate the Nodes to keep SA Sun pointing. Once commanded into fine reference pointing, the ACS will also use star trackers. The Node bus EPS provides electrical power during sunlit and eclipse periods through all phases of the mission where the Node is free flying. Sizing of the EPS system is driven by both thrusting maneuvers and long-duration eclipses. The SCS is considered part of the Node Payload, and interfaces with the Node bus avionics. Nodes have no direct communications with the ground and receive all commands and relay all data through the Hub. The IS payload communicates with the Node avionics through the IDPU. The Node avionics include a high-speed data recorder with enough storage to hold science data through several orbits, providing robust margins to handle anomalies.

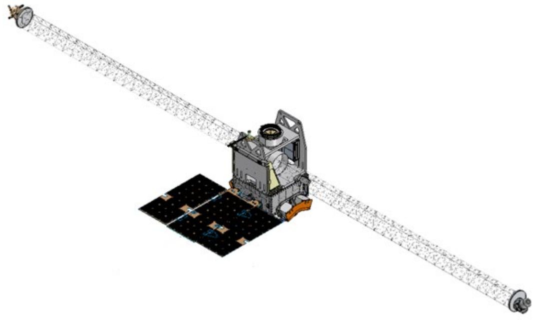


Figure 4: One of the HelioSwarm Nodes in the deployed science configuration.

Integrated System

The 8 Nodes are mounted to the ESPA ports on the Hub for launch, with the Nodes unpowered. The Hub and Node solar arrays are stowed, along with all of the magnetometer booms. This provides a compact configuration for the 9 spacecraft and utilizes a comfortable fraction of the LV fairing volume. This also allows for stacking of other ESPA rings above or below HS, if desired.

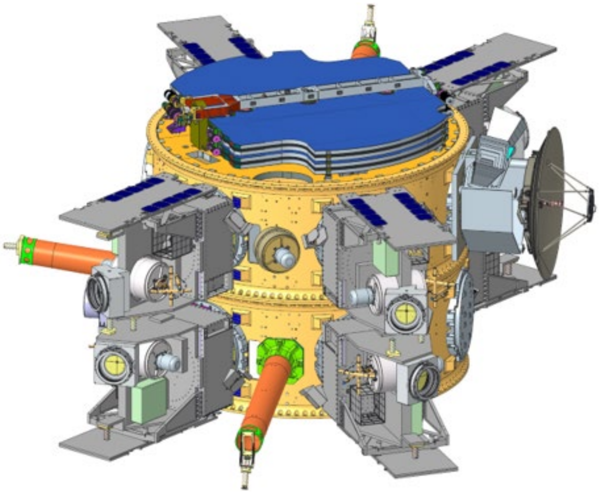


Figure 5: The HelioSwarm Observatory in the launch configuration.

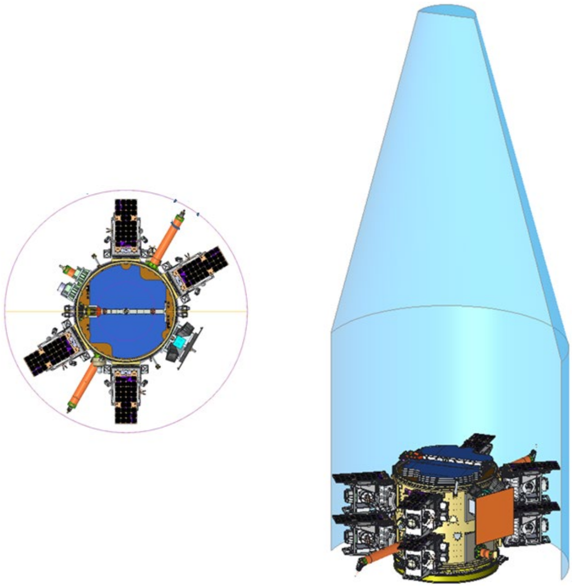


Figure 6: The HelioSwarm Observatory in the launch vehicle fairing.

Concept of Operations

HS launches with the Nodes powered off and attached to the Hub–this configuration is referred to as the Flight System (FS). The Launch Vehicle (LV) inserts the FS into the first of three phasing loops, with Hub maneuvers targeting a lunar swingby 29 days after launch. The Hub then coasts for 12 days before starting another series of maneuvers to set the science orbit. The final science orbit persists indefinitely, and the Hub requires no orbit maintenance maneuvers. The HS mission has a duration of 18 months, comprising the following phases: Launch and Early Operations (LEOPS), Phasing Loops, Transfer, Commissioning, Science, and Decommissioning. Operations for the first three phases are conducted in a manner consistent with single-spacecraft cis-lunar missions (such as LADEE or TESS). The HS transfer trajectory comprises a Phasing Orbit Insertion (POI), 3.5 phasing loops, and a non-propulsive lunar gravity assist (swingby) to raise perigee altitude and change inclination ultimately to obtain a P/2 Earth-Moon resonant orbit. The resonant state follows a Period Adjust Maneuver (PAM) on the first post-swingby perigee targeting the final science orbit period to half that of the Moon's orbit, a Perigee Setting Maneuver (PSM) at the following apogee, and a second PAM at the following perigee to complete the establishment of lunar resonance. In contrast to a direct lunar trajectory, phasing loops enable efficient mitigation of launch dispersions, an advantageous operational cadence, and improved OD accuracy in advance of lunar swingby. The lunar swingby adds energy to the geocentric orbit, raising perigee towards the science altitude while bringing inclination values into alignment with the design constraints. The swingby is a passive event, modifying HS's orbit with no fuel expenditure. The trajectory proceeds to apogee following the swingby, after which a perigee-apogee-perigee sequence of period adjust maneuvers (PAM1, PSM, and PAM2) bring the trajectory into P/2 resonance with stable lunar alignment.

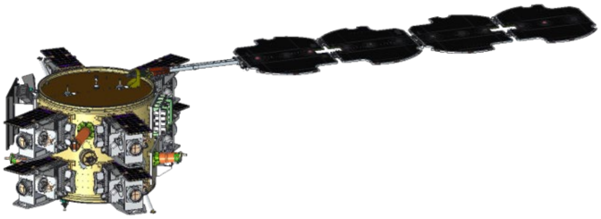


Figure 7: The HelioSwarm Hub with Nodes attached in the Transfer Phase configuration

Hub checkout begins after initial acquisition following LV separation and is completed in the Commissioning Phase. Once the FS achieves the stable P/2 resonant science orbit, operational focus shifts to Node separations/activations, Observatory commissioning, and swarm management. The Nodes are separated from the hub and activated one pair per orbit, enabling the MOS team to resolve potential systematic Node anomalies prior to separating others. Power-on and checkout of the IS are performed prior to the next pair of separations. This includes magnetometer boom deployments and instrument commissioning. Each Node pair finishes commissioning on the 8th day after separation, providing margin before the first Node maneuvers. The Science Phase starts after the 6th science orbit, once all 8 nodes are deployed, and lasts 12 months followed by a 1-month Decommissioning Phase. Science Phase operations are focused on return of science data and involve Observatory monitoring, crosslink session scheduling, and maintaining the swarm configuration. Near perigee, the Nodes are close to the Hub, making it ideal for science data downlink; near apogee, the Nodes are in ideal relative positions for science. The critical mission events for the FS are separation from the LV, initial acquisition of the Hub, and deployment of the Hub's SA and achievement of Sun-pointing. Telemetry is captured for all these events with SN coverage and DSN backup. Node separation and initial activation are not time critical as they can be re-scheduled on a subsequent orbit if missed. During each Science Phase orbit, there is an 8-hour DSN contact near perigee via the GCS with the HGA pointed towards the Earth. This pass is used to downlink science data, stored TLM, RT Hub telemetry, stored relative ranging data, and to uplink command products. In addition, there are five 2-hour DSN passes, via the combined LGA pair, per orbit with a 3-day maximum gap between passes. These passes are used to downlink Hub RT telemetry, stored relative ranging data, and Node and instrument SOH packets. The passes are also used for Hub tracking and to provide opportunities to uplink command products. The frequency of contacts ensures sufficient Hub tracking and Hub-to-Node relative ranging data to support OD and maneuver planning. D'Ortenzio, Bresina and Nakamura (2023) describe the operations approach for the mission.[3]

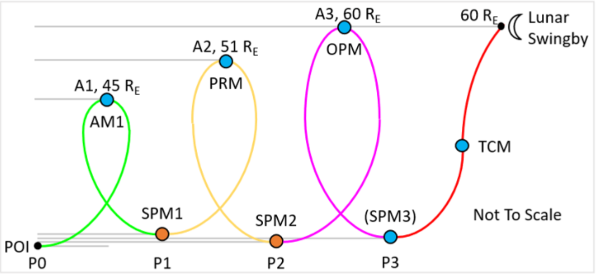


Figure 8: The HelioSwarm transfer phase uses Phasing Loops to achieve the science orbit.

Swarm Design

The HS Observatory accesses the regions of science interest with the 2-week, lunar-resonant, high Earth orbit (HEO). Since the science orbit is nearly inertially fixed (with a low rate of apsidal precession), apogee rotates through the solar wind (SW), foreshock, and magnetosphere-dominated regions as the Earth completes a single orbit of the Sun. Thus, the orbit allows the Observatory to sample the pristine SW and regions of strongly driven turbulence during the 12-month Science Phase. The spacecraft trajectories are designed to provide the spatial configurations, durations, and separations required for multiscale sampling of turbulent structures.[4] The individual Node trajectories result in each having a different orbit, producing repetitive cycles of motion relative to the Hub and each other. The orbits of each Node are designed so that the Observatory expands as it moves from perigee to apogee. As the swarm approaches apogee, the node trajectories naturally move the Observatory into polyhedral and 3D configuration. All eight Nodes perform regular small trim maneuvers to maintain the Observatory throughout the Science Phase. The orbit accuracies for the pairwise Node separations are validated by ground-based processing of the Hub-to-Node TOF ranging measurements combined with the Hub DSN tracking measurements. The orbit determination (OD) process is executed after each tracking data update, and the latest Node orbit states are propagated into the future to generate predicted orbit ephemeris for planning the next set of orbit trim maneuvers. HS leverages relative orbital motion to create a holistic, multi-satellite Observatory. Just as all satellites coast in orbital motion subject to the sum of Newtonian forces acting on them, HS's Nodes repeat their relative motion due to slight differences in their orbits, with occasional trim maneuvers to counteract perturbing forces. Node relative motions are designed to meet science requirements for Node pair baseline length, 3D baselines in three simultaneous scales, and simultaneous tetrahedra in ≥ 3:1 scale ratio, plus operational requirements for approaches by turns to within 200 km of the Hub for high data rate crosslink, max range, and keep-out radius for avoidance of conjunctions in consideration of predicted position accuracy. The swarm design allows robust responses to spacecraft and instrument anomalies during early and late stages of the prime mission, to ensure the science return.[5] Science orbit and swarm design both leverage eccentricity to use a portion of the trajectory arc near apogee where velocity is slowest to collect data in exposure to the solar wind and to take advantage of lower altitude and shorter relative ranges near perigee for science data crosslink and downlink.

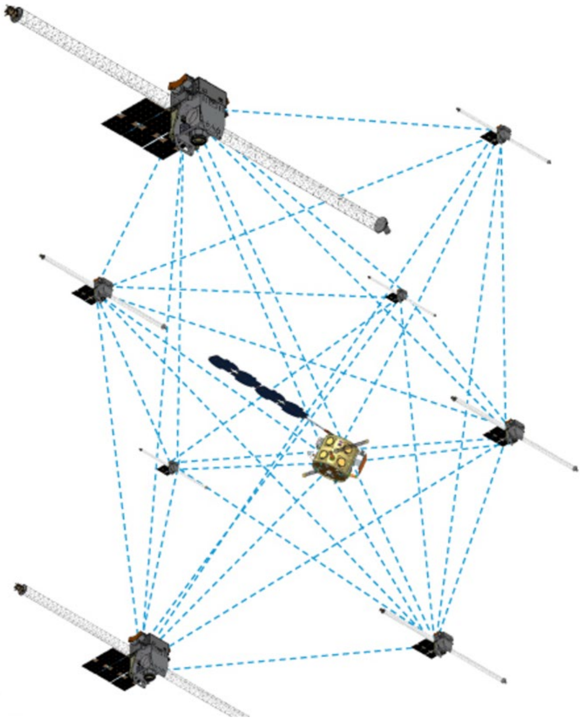
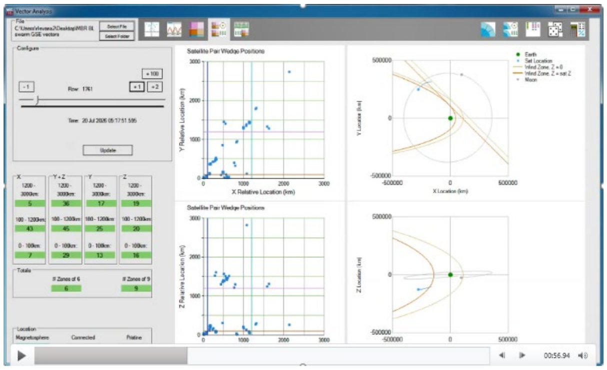


Figure 9: The HelioSwarm Observatory uses simultaneous multi-scale tetrahedra formations.

The baseline swarm trajectory design is the result of a very close collaboration between the HS science team and the HS Flight Dynamics team.[4,5] The swarm trajectory design is what enables the simultaneous multi-scale instrument observations that are the key to achieving the science goals.

An example of this close collaboration is the development of a flight dynamics visualization tool that captured the science requirements into a metric of success that the trajectory designers could use to evaluate their design choices. Figure 10 shows a screen capture from that dynamic tool.



C:\Users\...\Desktop\MBR BL swarm GSE vectors

Row: 1761

Time: 20 Jul 2026 05:17:51.595

X	Y+Z	Y	Z
1200 - 3000km: 5	1200 - 3000km: 36	1200 - 3000km: 17	1200 - 3000km: 19
100 - 1200km: 43	100 - 1200km: 45	100 - 1200km: 25	100 - 1200km: 20
0 - 100km: 7	0 - 100km: 29	0 - 100km: 13	0 - 100km: 16

Totals: # Zones of 6: 6; # Zones of 9: 9

Location: Magnetosphere Connected Pristine

Figure 10: The HelioSwarm science metrics are visualized during the swarm trajectory design.

Systems Engineering

The SE team is responsible for identifying growth threats and maintaining margins to accommodate unplanned growth with minimum design impact, as well as taking corrective action if necessary, across the entire project. To facilitate this task, Technical Performance Measures (TPMs) are used in three main ways on HS: 1) All TPMs are used in the verification burndown during Project V&V, 2) to allow the Project SE and Project Management to monitor technical progress on key items, and 3) for providing trending of mission critical items. A subset of TPMs of interest to the broader audience is included in Table 1. Additionally, at every major stakeholder interaction, HS provides a "PI Satisfaction Index" which is a color-coded scale comprised of a combination of current technical performance, science readiness, resources, risk burn-down, and the PI's subjective assessment. This index facilitates an intuitive introduction to the material about to be shared and quickly provides a top-level indication of the state of the Project.

Table 1: HS TPMs

Metric	Hub	Node
Mass (in Science Orbit w/instruments)	727 kg	73 kg
	Total FS Launch Mass: 1614 kg	
Propulsion	252 m/s capability (62 % tank margin)	50 m/s capability (21% tank margin)
Telecom	S-band 5775 Mbps to DSN	S-band 250 kbps to Hub
Pointing	3-axis, 0.026° control (>1700% margin)	3-axis, 0.069° control (>600% margin)
Power	1165 W EOL (113% margin) 96 A-hr battery (30% margin)	200W EOL (21% margin) 13.2 A-hr battery (25% margin)
C&DH	26 GB onboard storage, 111% margin	71 GB onboard storage, x49 margin
Science Data Sufficiency	3D-PSW (500 hrs): **851 hrs**; 3D-Strongly Driven Turbulence (500 hrs): **1608 hrs**; Polyhedral-PSW (100 hrs): **1040 hrs**; Polyhedral-Strongly Driven Turbulence (100 hrs): **1444 hrs**	

THE FUTURE

NASA's Science Mission Directorate selects MIDEX missions not only for the science return, but also to test and mature new technologies and approaches for future larger missions. Technology demonstration missions can mature and prove the heritage of individual elements, of course, but new approaches face their greatest challenge in the crucible of accomplishing significant science objectives. The Heliophysics Decadal report has called for ambitious science missions that are enabled by swarm implementations.[6,7] The HelioSwarm mission may serve as a pathfinder for larger swarm missions in the future.

Acknowledgments

This paper reflects the work of the entire HelioSwarm team. We would like to acknowledge the partner organizations making up the HS team: University of New Hampshire, NASA Ames Research Center, Northrop Grumman Space Systems, Blue Canyon Technologies, Smithsonian Astrophysical Observatory, Imperial College London, University College London/Mullard Space Science Laboratory, Institut de Recherche en Astrophysique et Planétologie, Laboratoire d'Astrophysique de Bordeaux , Laboratoire de Physique des Plasmas, Laboratoire de Physique et Chimie de l'Environnement et de l'Espace, University of California Berkeley and NASA Goddard Space Flight Center; Funding provided by NASA, CNRS, CNES, and UKSA. This mission is managed under the Explorers Program Office at NASA Goddard Space Flight Center[2] and is a part of the NASA Science Mission Directorate's Heliophysics Division.

References

List and number all bibliographical references at the end of the paper. When referring to references in the text, type the corresponding reference number in superscript form as shown at the end of this sentence.1 Use the **References** style for formatting citations, as shown in the following examples:

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