



THE NATURE OF TURBULENCE IN SPACE PLASMAS

*A Multispacecraft Mission to Study Turbulence in
Space Plasmas*

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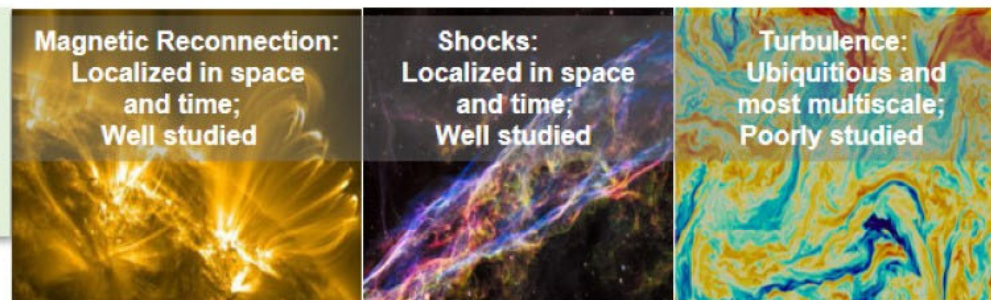


Background: Resolving Turbulence Across Scales



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 – understanding requires multipoint cross-scale measurements of the plasma physics

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?



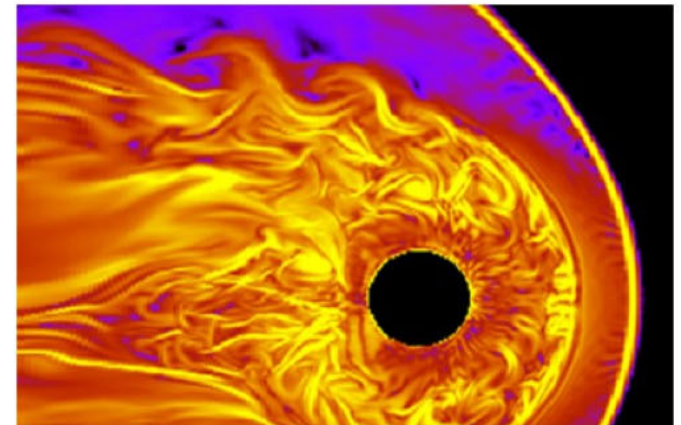
Turbulence is Multiscale Disorder

- Turbulent flow is one in which a gas, fluid, or plasma undergoes irregular fluctuations and mixing
- Turbulent flows are multiscale; energy injected at largest size scale cascades to smaller scales, eventually converting the kinetic energy in the flow into thermal energy of the constituent medium
- Turbulence 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



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



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

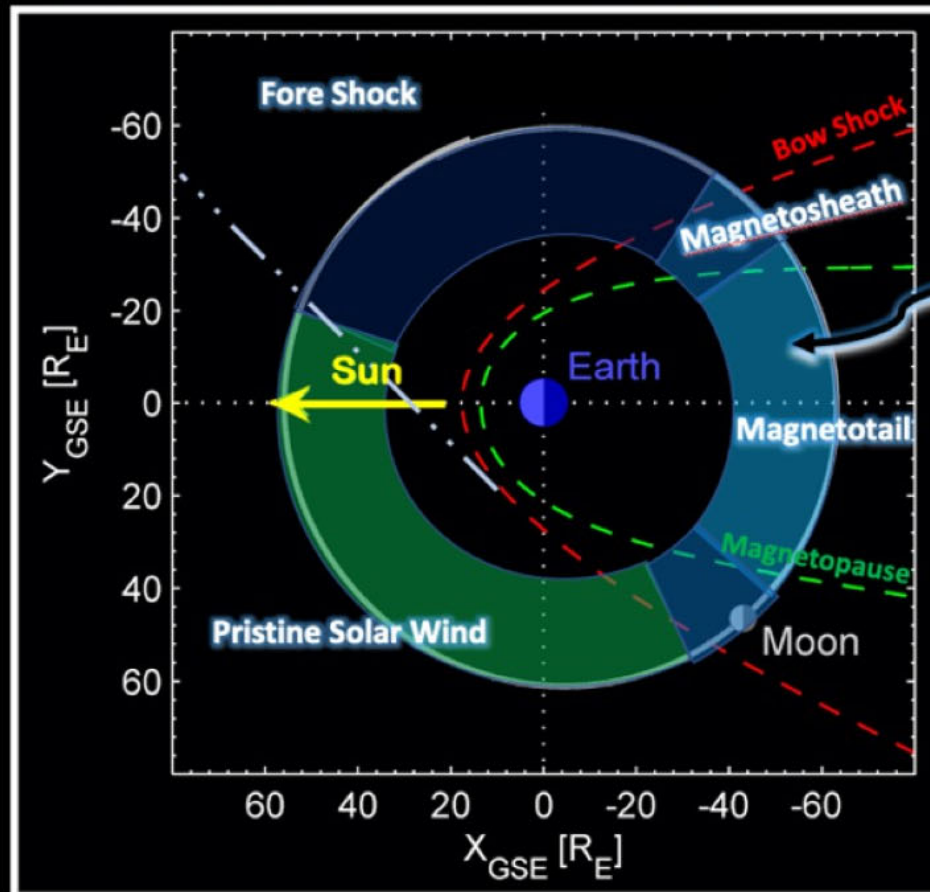
HelioSwarm's Targeted Science Regions



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

HelioSwarm Science Goals and Objectives



Science

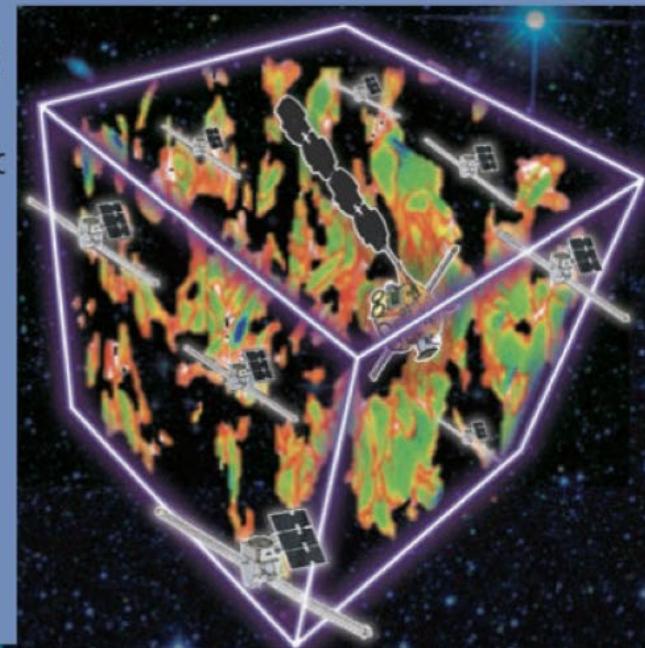
HelioSwarm science is tightly aligned with NAS 2013 Heliophysics Decadal Survey and NASA SMD Priorities: Turbulence identified as a Decadal Science Goal ("Understand the origins and effects of turbulence") and a Decadal Imperative ("Implement . . . a multispacecraft mission to address cross-scale plasma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

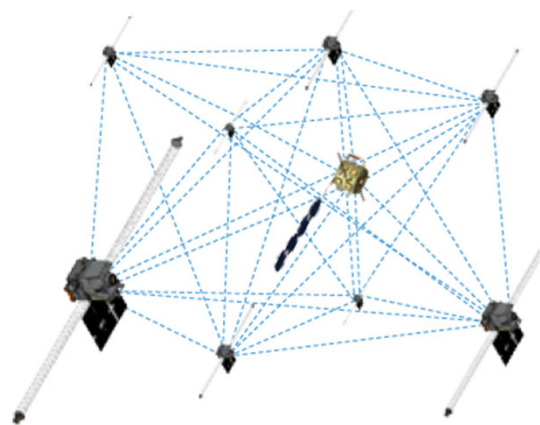


HelioSwarm's first-ever simultaneous multipoint, multiscale measurements disentangle spatial and temporal variations in solar wind plasmas that connect MHD scale turbulence with sub-ion scale heating.

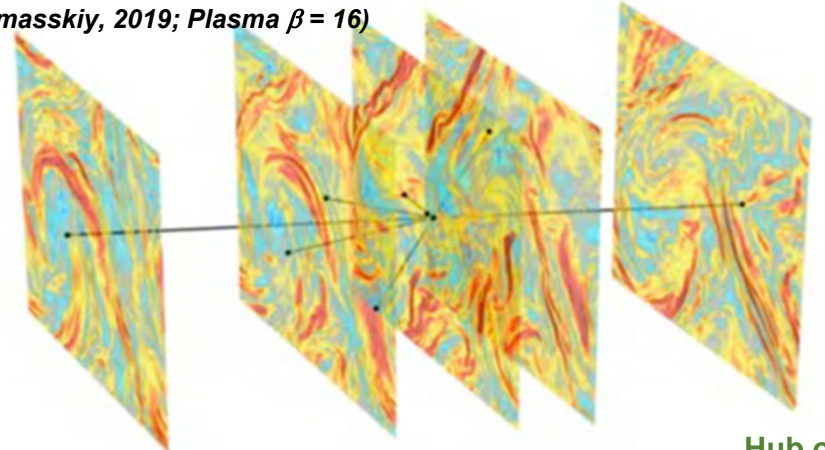
Simultaneous Multi-Scale Measurements



- HS Observatory measurements provide unprecedented views of space plasma turbulence – not just *better* but **transformative**
- Observatory enabled by state-of-the-art instruments and high spacecraft heritage; **the mission innovation is in the swarm implementation**



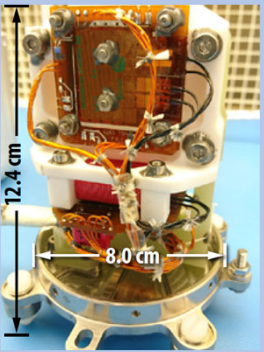
(Arzamasskiy, 2019; Plasma $\beta = 16$)



Hub only

Hub and Nodes

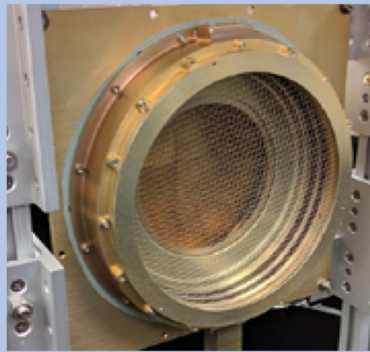
MAG – Fluxgate
(Imperial College)



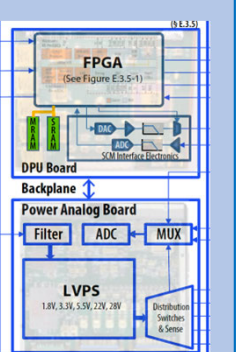
SCM – Search Coil
(LPP/LPC2E)



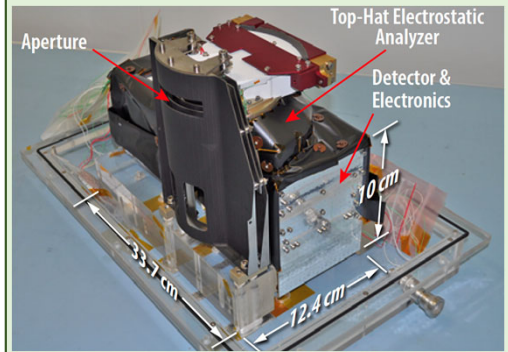
FC – Faraday Cup
(SAO/Draper/UCB)



IDPU – Inst. Dig. Proc. Unit (UNH)



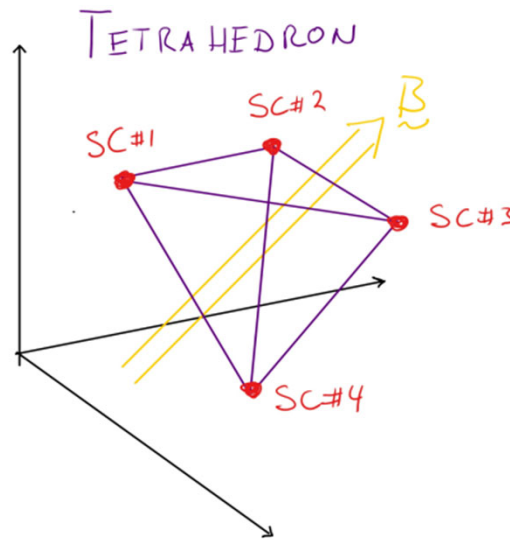
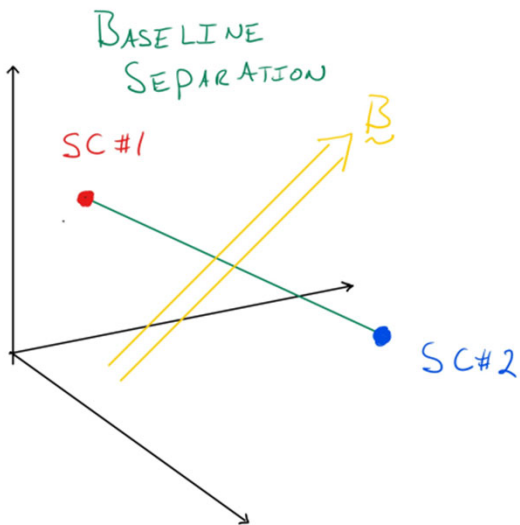
iESA – Ion Electrostatic Analyzer
(IRAP/LAB/UNH/MSSL)



Student Electron ESA (UCB) (UCB)



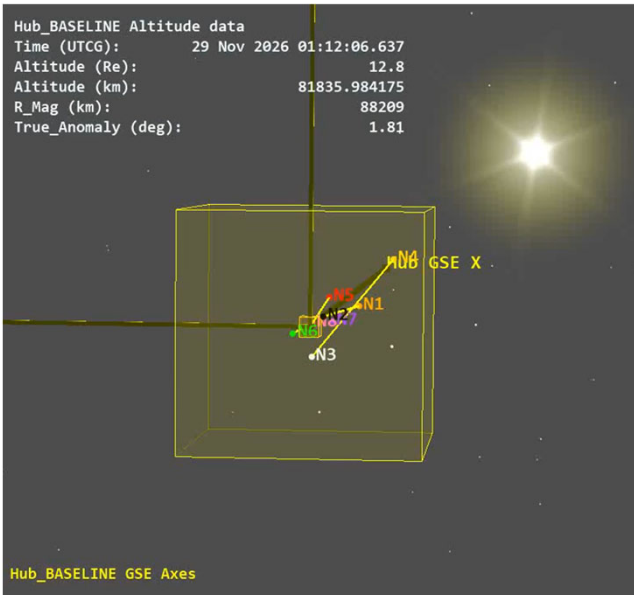
HelioSwarm inter-spacecraft geometries



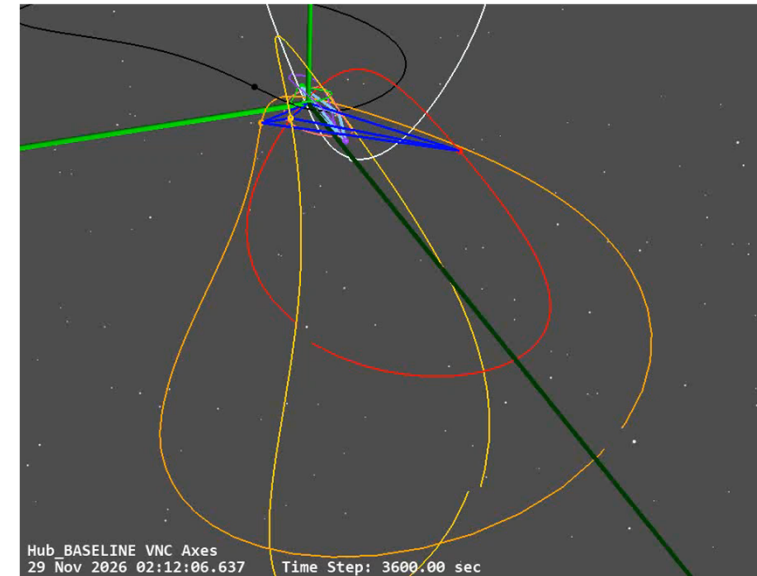
- More spacecraft fundamentally yields more
- baselines scaling as $N(N-1)/2$
- polyhedral shapes [e.g. the number of tetrahedra scaling as $C(N,4)=N!/(4!(N-1)!)$]
- The more baselines and polyhedra an observatory measures, the more scales can be covered, and the more data is produced for statistical 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.

# 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

HelioSwarm 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.

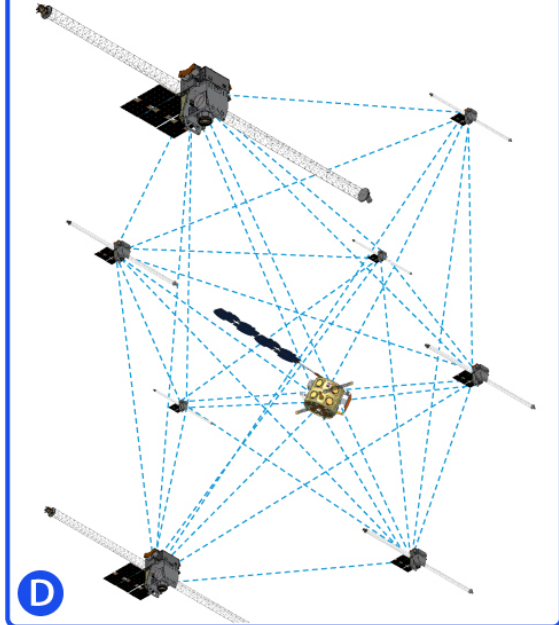
Curlometer & Gradient Methods: Multipoint methods for constructing current density/intermittent structures from spatially distributed measurements.

Tailored Application of Orbital Dynamics



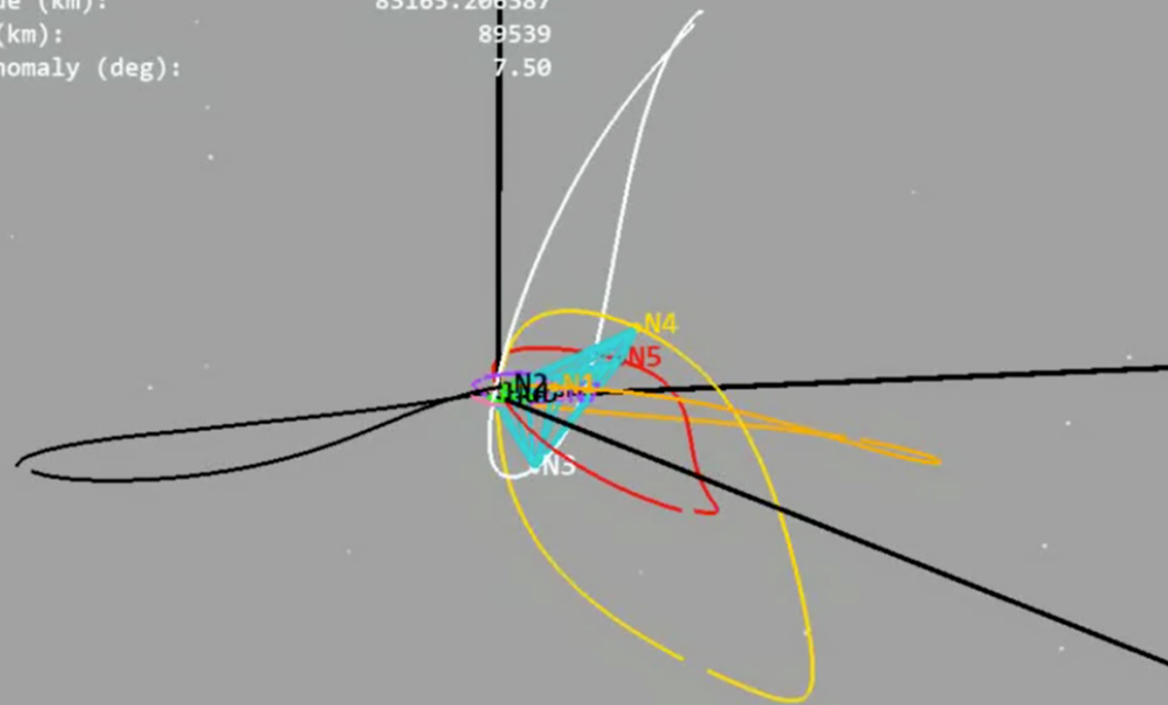
HelioSwarm Observatory:

Provides 1st measurement of energy cascade rate at multiple scales simultaneously



B-01L

```
Hub_BASELINE Altitude data
Time (UTCG):      21 Sep 2026 06:07:56.729
Altitude (Re):    13.0
Altitude (km):    83165.206387
R_Mag (km):       89539
True_Anomaly (deg): 7.50
```



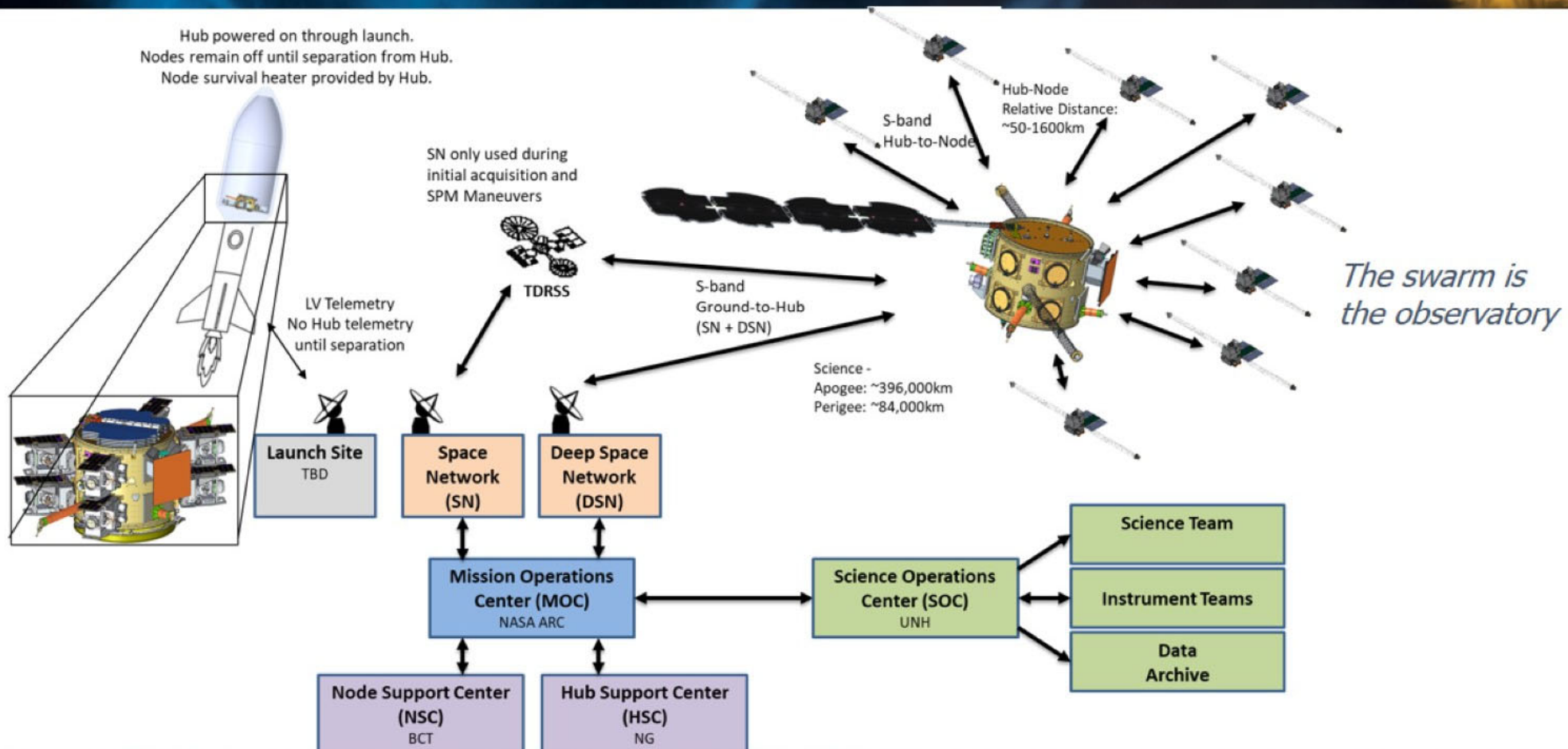
```
Hub_BASELINE VNC Axes
21 Sep 2026 06:07:56.729
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Trajectories of 9 co-orbiting spacecraft produce required Observatory configurations

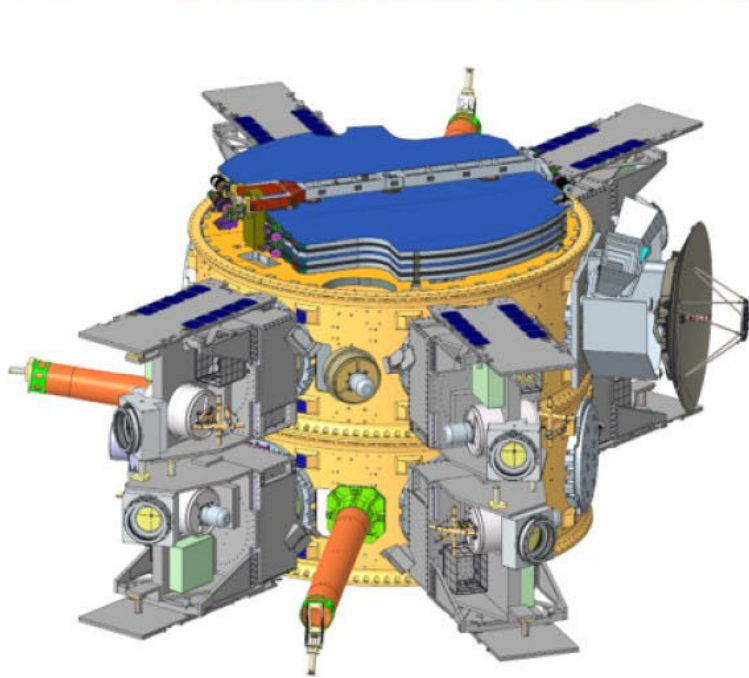
Mission Architecture



Hub powered on through launch.
Nodes remain off until separation from Hub.
Node survival heater provided by Hub.



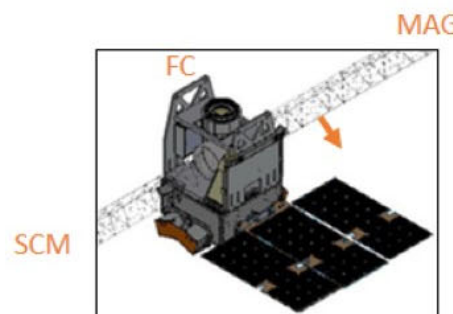
Flight Segment



Launch Configuration

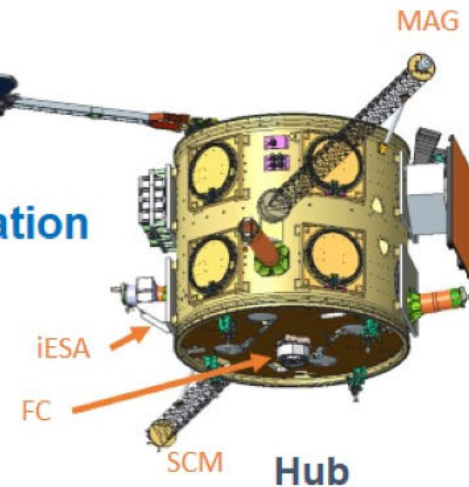


Transfer to Science Orbit



Node (x8)

Science Configuration



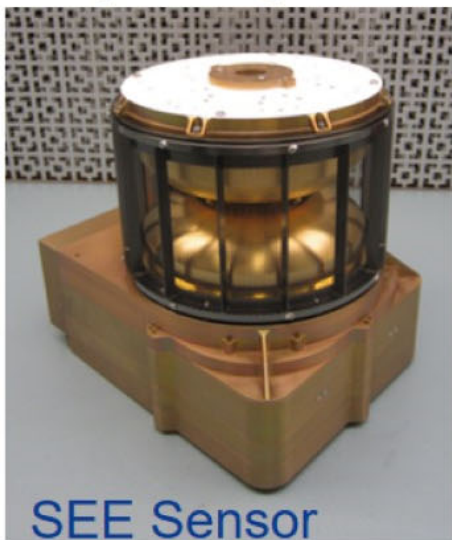
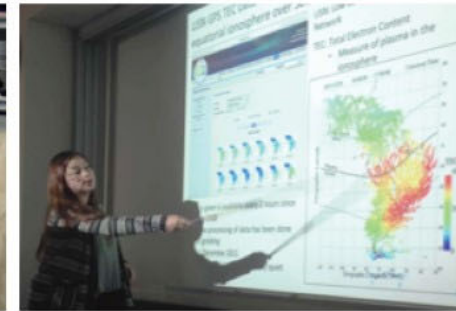
Student Collaboration: The SEE project



SEE is a **student-led, high-heritage** electron spectrograph.

The philosophy is an instrumentation-focused, student-run project that spans both engineering and science disciplines at multiple levels of student engagement.

SEE recruits students via four different programs across community college, undergraduate, and graduate levels



SEE Sensor



Block Diagram of SEE + SIDPU



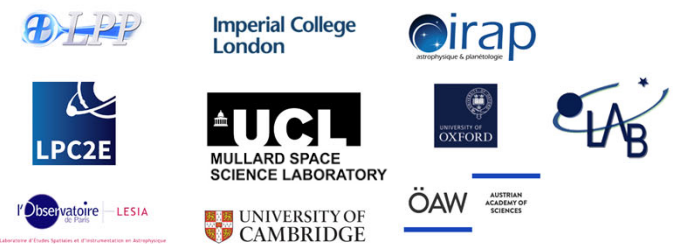
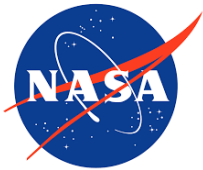
SIDPU

- The SEE SCO consists of a **high-heritage electron electrostatic analyzer** (SEE Sensor) and a high-heritage processing unit (SEE Instrument Digital Processing Unit, SIDPU)
- **Incremental changes from heritage designs** ensure likelihood of success while **granting students ownership**.

Heritage: *Parker Solar Probe, HERMES, SWFO-L1, ESCAPADE, MAVEN, THEMIS...*

Italicized Missions have SEE leader contributions

Roadmap of HS Institutions



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 ● PRIMARY OPERATION ● EXTENDED OPERATION

- | | | | | |
|--|---|---|--|---|
| <ul style="list-style-type: none"> AWE (ISS) Carruthers Geocorona Observatory ESCAPADE (2) EUVST (JAXA) EZIE (3) GDC (6) | <ul style="list-style-type: none"> HelioSwarm (9) HERMES (Gateway) IMAP MUSE PUNCH (4) SunRISE (6) TRACERS (2) | <ul style="list-style-type: none"> Parker Solar Probe Solar Orbiter (ESA) | <ul style="list-style-type: none"> ACE AIM GOLD (SES-14) Hinode (JAXA) IBEX ICON IRIS MMS (4) RAD (Curiosity) | <ul style="list-style-type: none"> SDO STEREO THEMIS-ARTEMIS (2) THEMIS (3) TIMED Wind Voyager (2) |
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