Revealing the Multiscale Nature of Turbulence in Space Plasmas with an Innovative Swarm of Spacecraft

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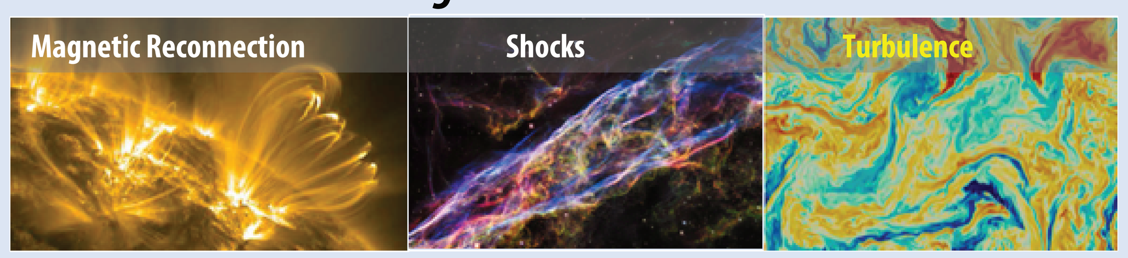
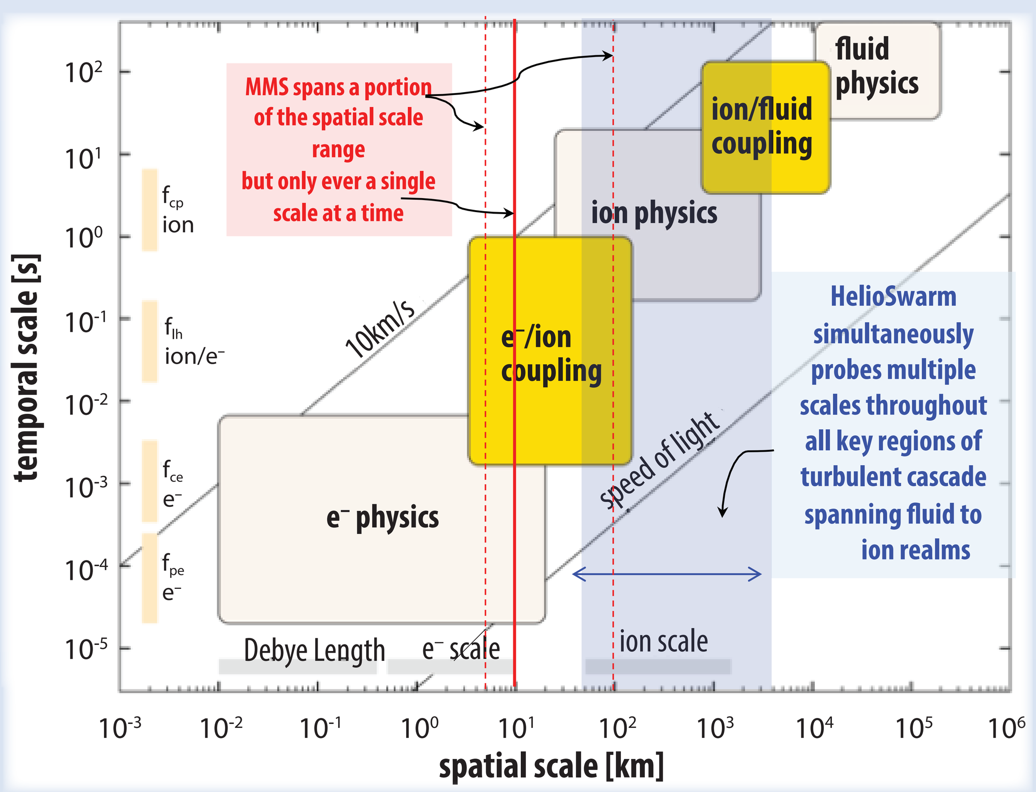
Abstract: Turbulence is fundamentally a multiscale phenomena, with energy, mass, and momentum being transported across both spatial and temporal scales. In a magnetized collisionless plasma, there are unresolved questions about the structure of the turbulent transfer of energy, as well as how the energy is extracted from the cascade and dissipated as heat in the constituent charged particles. The plasma in the solar wind acts as an accessible natural laboratory to study these processes, and much progress has indeed been made since the dawn of the space age in understanding turbulence via in situ observations of turbulent plasmas near Earth. However, to date, these observations have been limited to a single, or at best, a tight cluster of points, leading to ambiguities in at what scales energy is contained, how it is transported, and by what mechanism it is dissipated.

In this presentation, we describe a heliophysics mission concept aimed at understanding turbulence that is enabled by a swarm of small satellites. The proposed "HelioSwarm" mission will measure turbulent fields and flows and charged particles simultaneously at many points spanning size and time scales from the fluid to sub-ion regime. In doing so, we will be able to disentangle how the turbulence depends on time and space, directly observe the change in internal energy in the plasma, and definitively capture the dynamic relation between turbulence and structures. While the processes under examination are universal, arising throughout our solar system and universe, they are difficult to reproduce in either terrestrial laboratories or numerical simulations, meaning that the only a multipoint observatory in the near-Earth heliosphere will be able to study them in sufficient detail to discern the underlying physics. In this talk, we highlight the enabling role that small satellites play in providing closure on these long-standing but critically important science questions.

Science Motivation:
Resolving Turbulence Across Scales



Three universal plasma physics 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**



In situ measurements of space plasmas have been limited to either a single point (e.g., ACE or any single S/C) or to a single scale (MMS, Cluster) – **competing turbulence theories thus remain fundamentally unresolvable**

HelioSwarm Science Goals and Questions

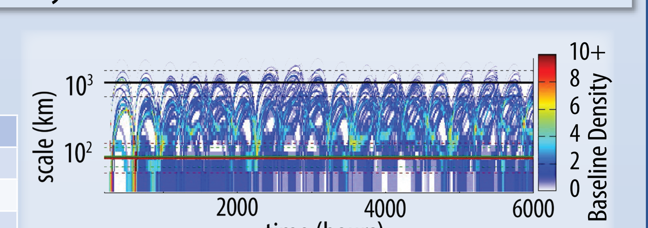
Goal #1: *Quantify the 3D spatial distribution of homogenous turbulence in a collisionless plasma* →
- *How does energy transfer across length scales, and how is this transfer controlled by the background magnetic field?*
- *How do bulk plasma conditions modify this transport?*

Goal #2: *Determine the dominant mechanisms of damping and dissipation of the turbulent cascade* →
- *What physical mechanisms transfer energy between turbulent fields, flows, and charged particles?*
- *What controls ion/electron energy partitioning?*

Goal #3: *Quantify the spatial and temporal distribution of inhomogeneous turbulence* →
- *How does strongly driven magnetospheric turbulence differ from that of the pristine solar wind?*
- *How do interplanetary shocks and CMEs drive turbulence?*

How many spacecraft are required?

				Threshold				Baseline	
Size of Swarm (Hub + Nodes)	4	5	6	7	8	9	10	11	12
Number of Nodes	0	4	5	6	7	8	9	10	11
# of unique S/C pair separations	6	10	15	21	28	36	45	55	66
# of unique 4-S/C tetrahedra	1	5	15	35	70	126	210	330	495



Simultaneous distributed measurements enable complementary analysis techniques that address outstanding questions about the nature of the turbulent cascade and its dissipation. Two-point correlations with spatial and temporal lags will reveal dynamic structures inaccessible to single points observations. These separations enable *in situ* measurement of anisotropic energy transfer rates simultaneously in the inertial and dissipation ranges, and allow application of wave-telescope and other multipoint signal resonator techniques to identify the presence of waves and coherent structures at multiple scales.

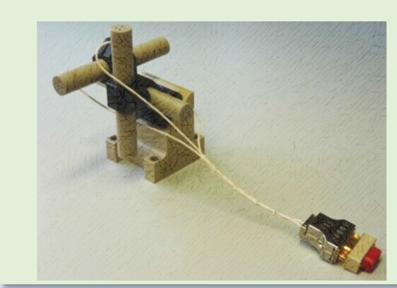
Node spacecraft. (Not to scale)

HelioSwarm Instrument Suite
High-TRL yet Optimal For Measurement Requirements

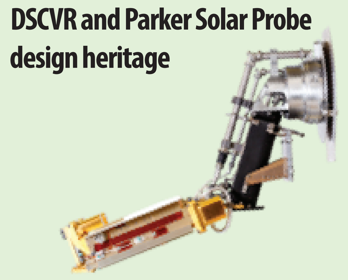
Each S/C (hub and nodes) hosts a Faraday Cup, a Search Coil Magnetometer, and a Fluxgate Magnetometer; in addition, the hub also hosts electron and ion Electrostatic Analyzers

Fluxgate Magnetometer (FGM) [ICL]
- DC (to 64Hz) magnetic field dynamic range in SW from ±128 nT with 4 pT sensitivity. Additional ranges span ±>50,000 nT
- Noise floor ~10pT/√Hz at 1 Hz
- **Solar Orbiter and JUICE design heritage**

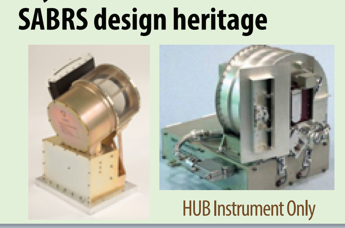
Search Coil Magnetometer (SCM) [LPP]
- AC Magnetic field from 1 Hz (calibrated down to 0.03 Hz) to 6 kHz
- Sensitivity of 2 pT/√Hz at 10 Hz; 0.3 pT/√Hz at 100, and 0.05 pT/√Hz at 1 kHz
- **MMS and JUICE design heritage**



Faraday Cup (FC) [UMich/SAO]
- Measurements at >10 Hz cadence of:
  - SW velocity: 200 - 1500 km/s at ±3%
  - SW density: 0.1 to 200 cm^{-3} ±10%
  - SW p+/He++ ratio: 0 - 100% at ±10%
- Energy/charge range: ~100V to ~ 4kV
- **DSCVR and Parker Solar Probe design heritage**



Electrostatic Analyzers (ESA) [LANL & UCB]
- Ion ESA (LANL):
  - Energy range: 260 eV to 36 keV
  - Energy resolution: dE/E ~ 5%
- Electron ESA (ESA):
  - Energy range: 10 eV to 10 keV
  - Energy resolution: dE/E ~ 12%
- 10 hz cadences
- **Ulysses, ACE, Genesis, IMAP, and SABRS design heritage**



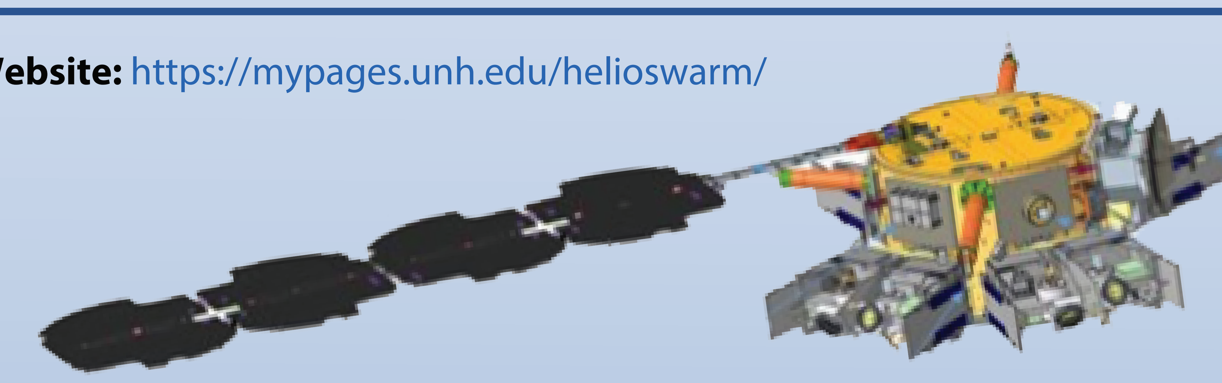
HUB Instrument Only

Take-Away!

HelioSwarm science highly aligned with NAS 2013 Solar and Space Physics Decadal Survey and SMD Priorities: Turbulence features prominently in all three disciplinary areas of Heliophysics (SH, SWM, and AIM) in the science goals, imperatives, and throughout the text.

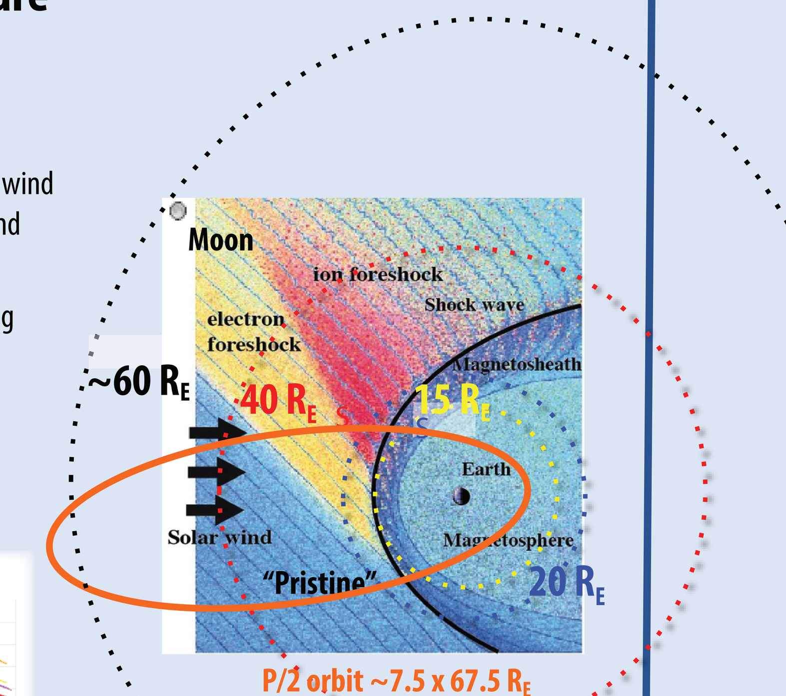
HelioSwarm's simultaneous multipoint measurements across length scales, ranging from the inertial through the transition region, provide the critical observations required for scientific closure. The Threshold and Baseline concepts offer 1 or 2 orders of magnitude more tetrahedral combinations than single-scale configurations.

Mission Website: https://mypages.unh.edu/helioswarm/

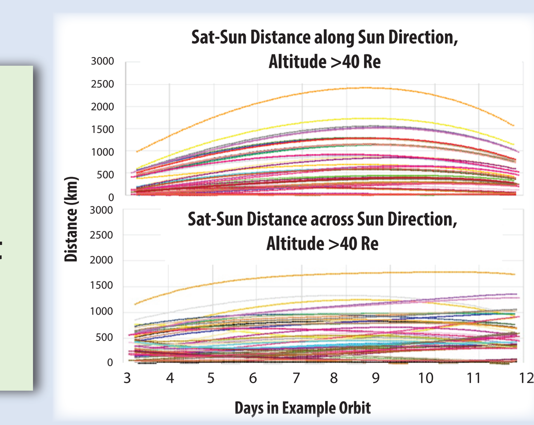


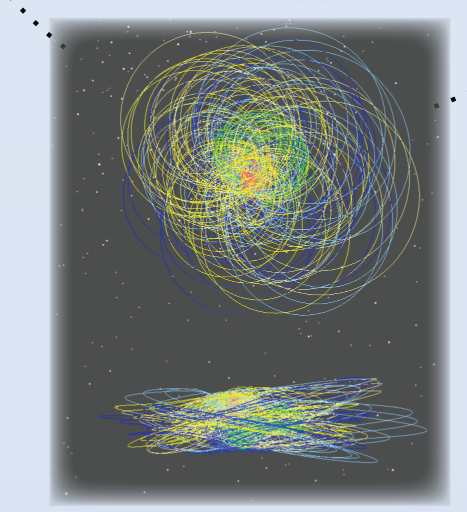
Mission Architecture

- **Swarm orbit:** constrained by requirement to sufficiently sample pristine solar wind (<40 R_E) "uncontaminated" by electron and ion foreshocks, magnetosheath, and magnetosphere.
- **P/2 lunar resonant orbit** comprising one "hub" (ESPA ring) and ten coorbiting "nodes" (small satellites) carried along by hub into final orbits.
- **Swarm configured through orbital design and on-board propulsion** to produce inter-spacecraft separations both along and across the Sun-Earth; *"Threshold" science can be met with four fewer nodes – science return degrades gracefully and robustly.*

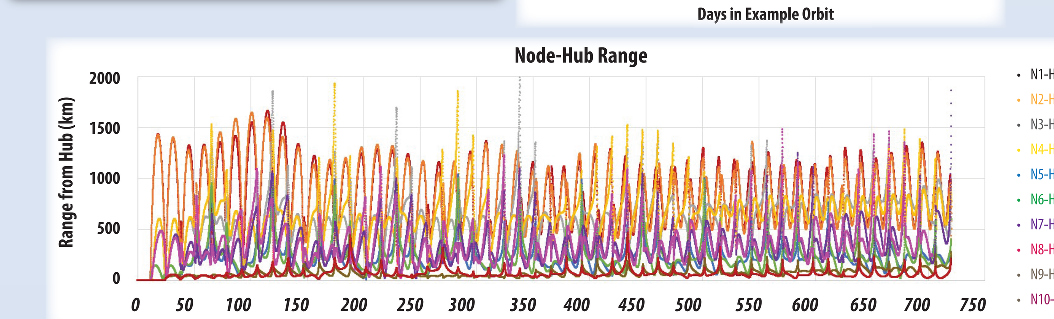


HelioSwarm is optimized for simultaneously probing multiple spatial scales ~50 to ~3000 km, exploring all regions of turbulent cascade that connect fluid scale processes with sub-ion scales.



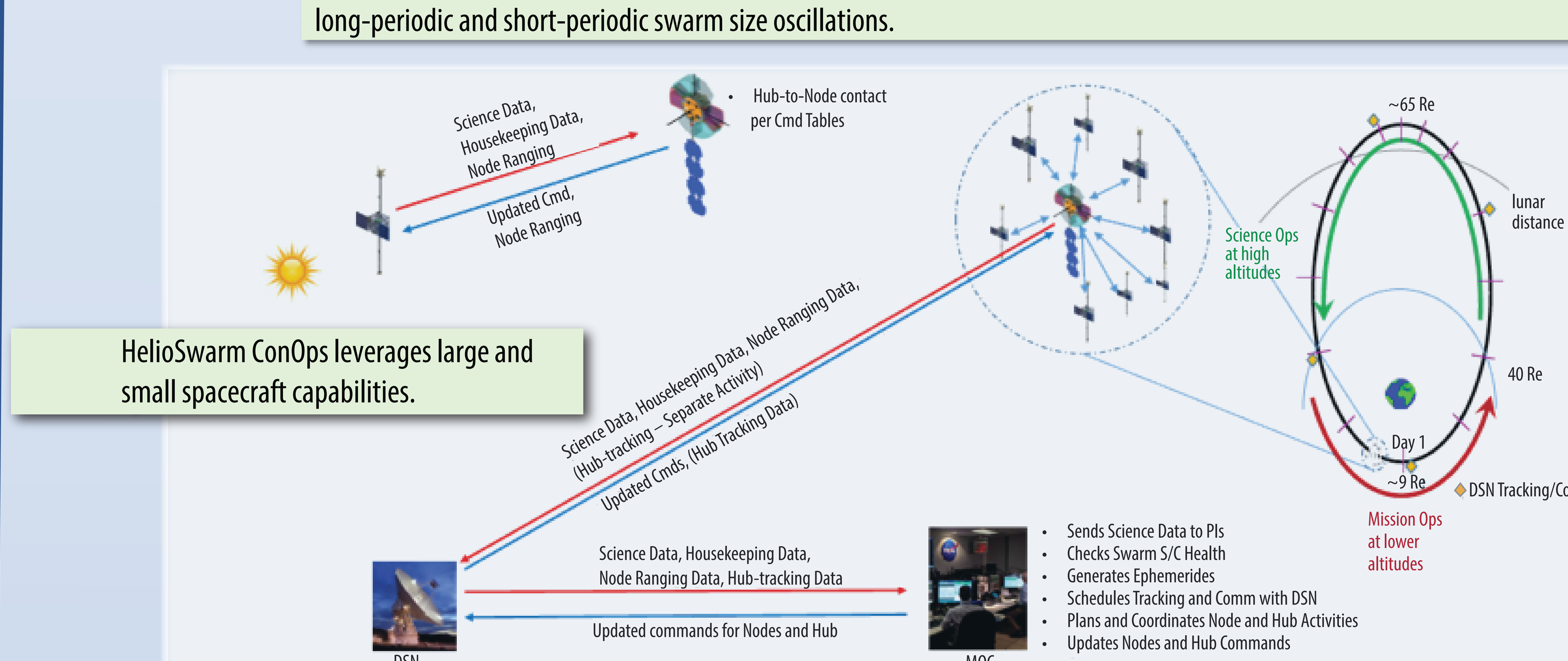


Bottom Left: Example node-hub ranges over the 2-year mission. **Top Left**: Example node-node ranges. **Right:** Example of swarm member's motion relative to the hub (top view and side view). Deployment may be optimized to produce specified long-periodic and short-periodic swarm size oscillations.



HelioSwarm ConOps leverages large and small spacecraft capabilities.

A large spacecraft carries the smallsats swarm to their destination orbit, deploys them, and then supplies communications relay functions to Earth; operated as swarm: nodes communicate with hub, hub with ground. Maneuvers occur once per orbit (typically 0.01–0.1 m/sec); cumulative delta-V budget over a 2-year mission is <20m/sec.



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