Revealing the Multiscale Nature of Turbulence with a Spacecraft Swarm
Mission Website: https://mypages.unh.edu/helioswarm/

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PRESENTED AT:

SCIENCE

The three universal plasma physics processes above are all highly dynamical, involving couplings between vastly separated scales, ranging from fluid (MHD) scales to microphysical (electron) scales. Turbulence drives the solar wind and controls the transport of energetic particles. A deeper understanding of turbulence is thus essential for understanding the origin of the solar wind and accurately modeling space weather. Turbulence is also critical to some of the most important processes in astrophysics - the formation of stars and planets, momentum transport and heating in accretion flows, dynamo generation of magnetic fields, and generally how cosmos gets hot.
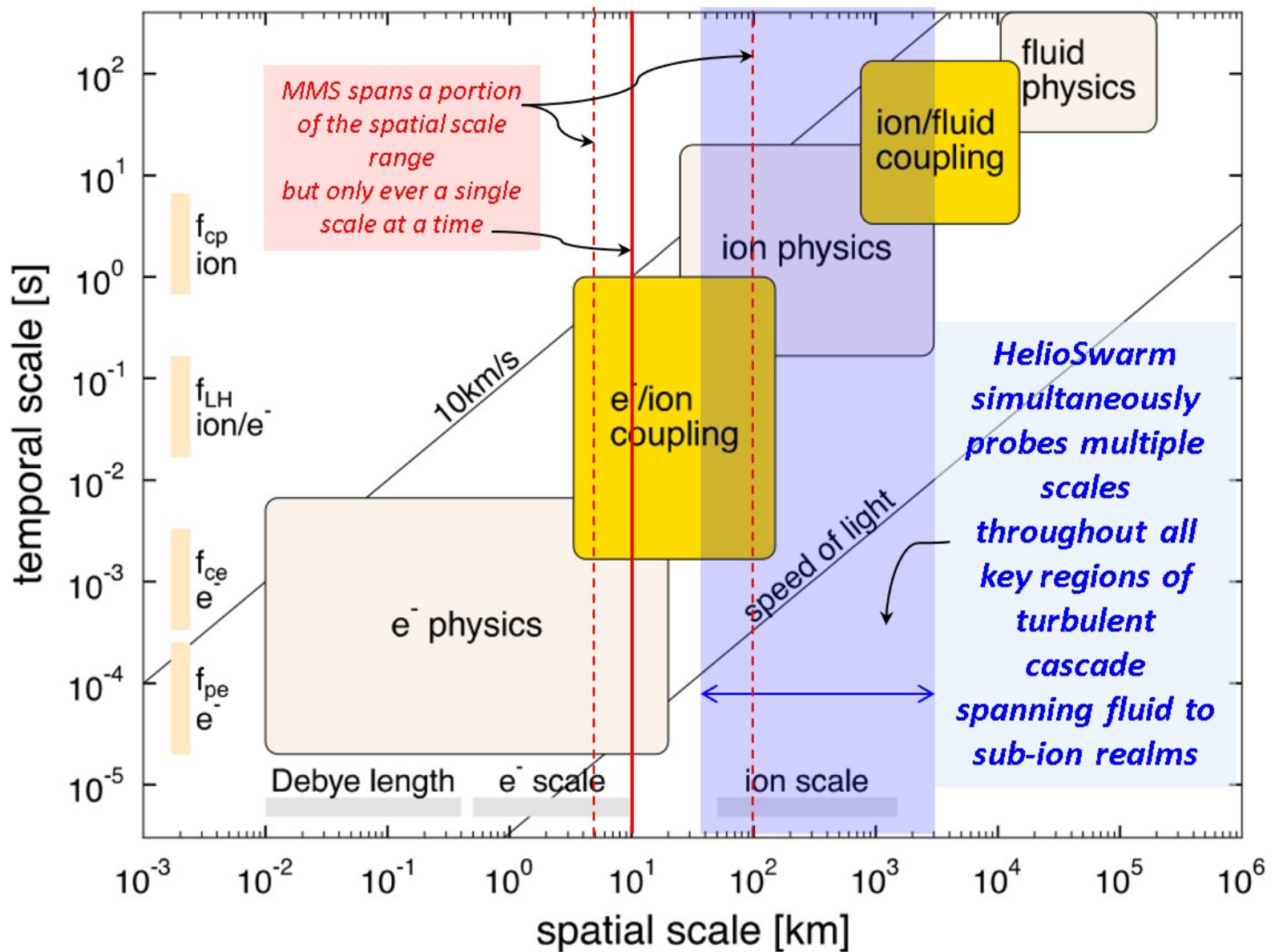
Understanding turbulence requires multipoint cross-scale measurements of a plasma. In situ measurements of space plasmas represent the best way to study these phenomena, but have been limited to either a single point (e.g. ACE, Wind, or any single s/c) or to a single scale (MMS, Cluster) - competing turbulence theories thus remain fundamentally unresolvable.

To distinguish between these proposed discriptions of turbulence, we propose flying a swarm of spacecraft, whose spatial distribution will cover inertial and ion kinetic scales. The heliosphere is the only location where we can measure high-dynamic-range turbulence in collisionless plasmas. Our proposed mission, HelioSwarm, will complete the experimental characterization of plasma turbulence that previous missions have begun, by disambiguating how fields vary in space and time across a large range of scales.

MISSION SUITABILITY I

The movies and figures below and at right (Mission Suitability II) show the evolution of key aspects of the swarm that are relevant to the science.

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

[VIDEO] https://www.youtube.com/embed/884sDuKzr24?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0
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How many nodes are required? Note that "threshold" science can be met with four fewer nodes – science return degrades gracefully and robustly

				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

The figure below demonstrates the coverage of the relevant baselines (spacecraft pair separations) as a function of mission time.
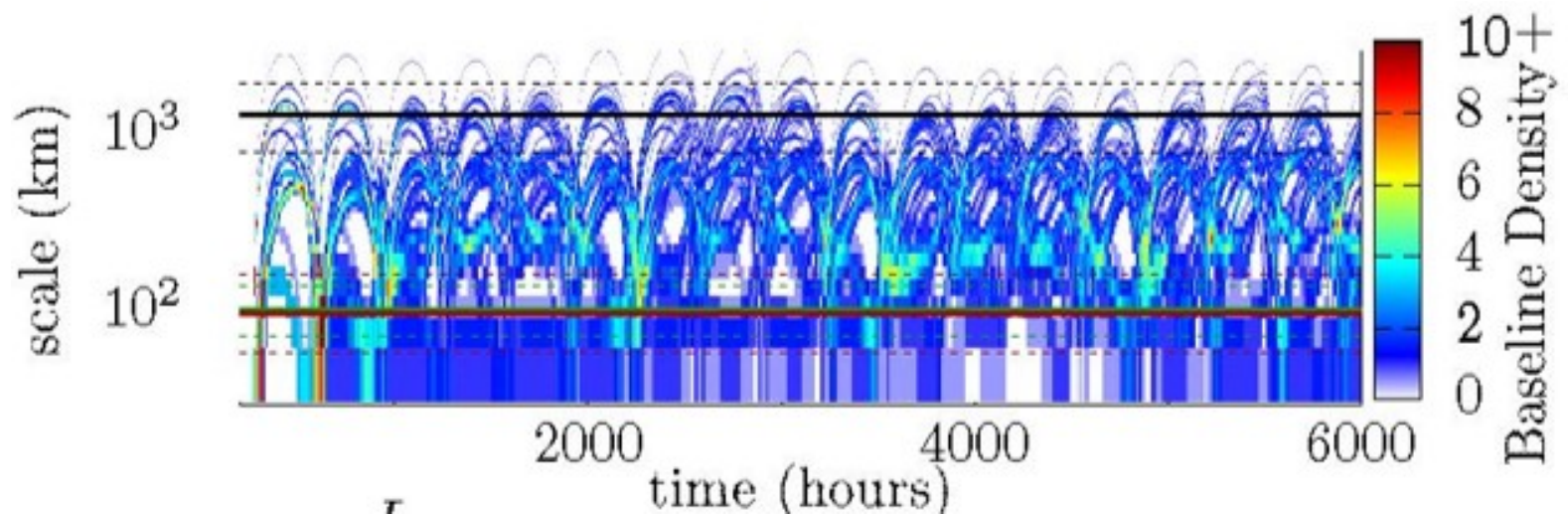
The figure below provides insight to the accumlated temporal coverage of simultaneous crosscale measurements as a function of number of swarm elements.
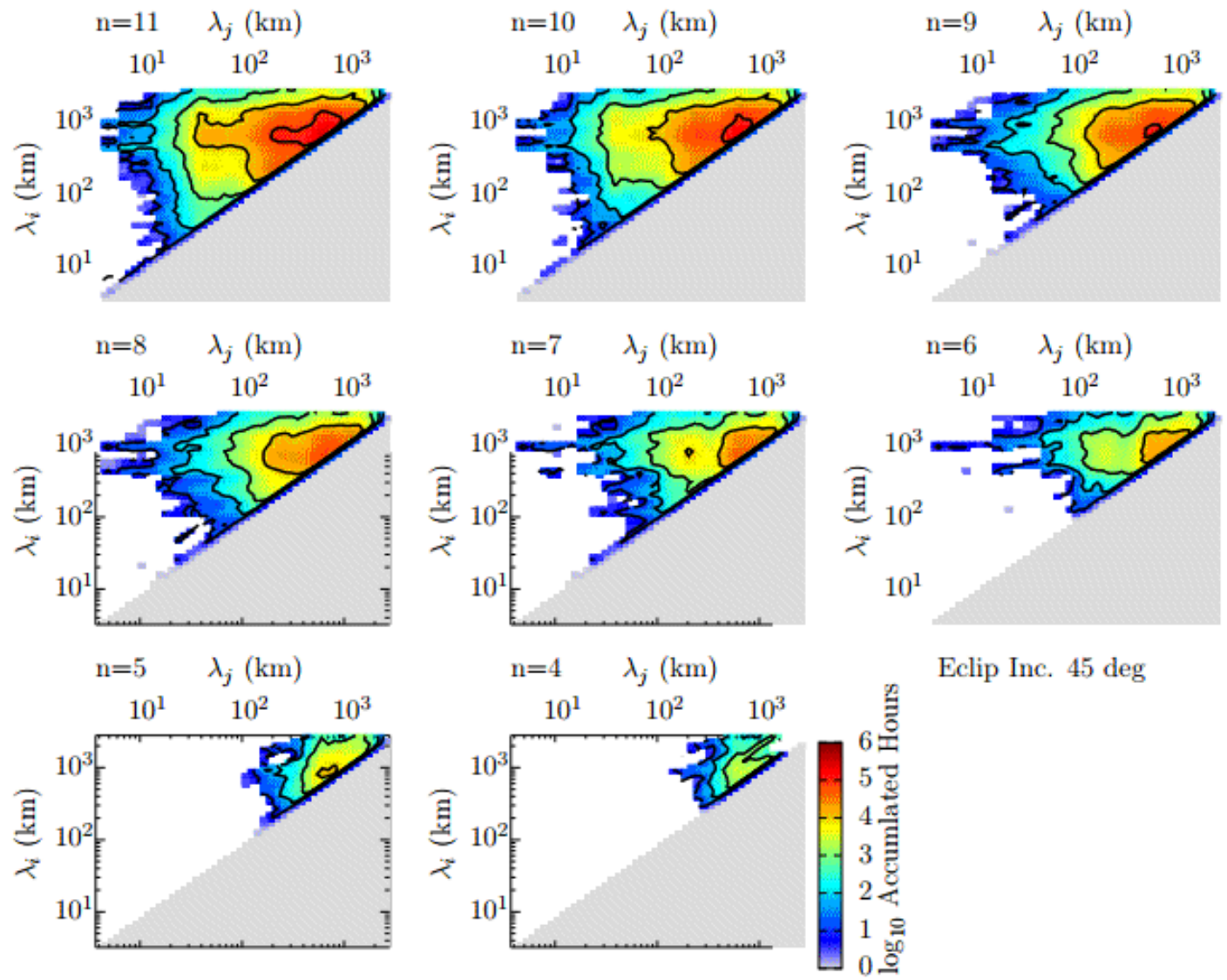
The figure below shows the number of baselines in different scale ranges for different numbers of swarm elements.

Eclip Inc 45 deg

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**
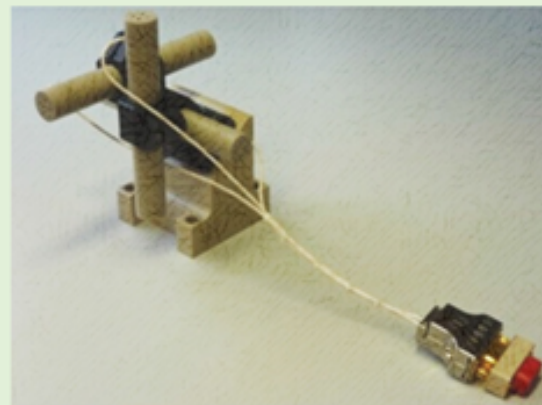
Faraday Cup (FC) [UMich/SAO]

- 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**
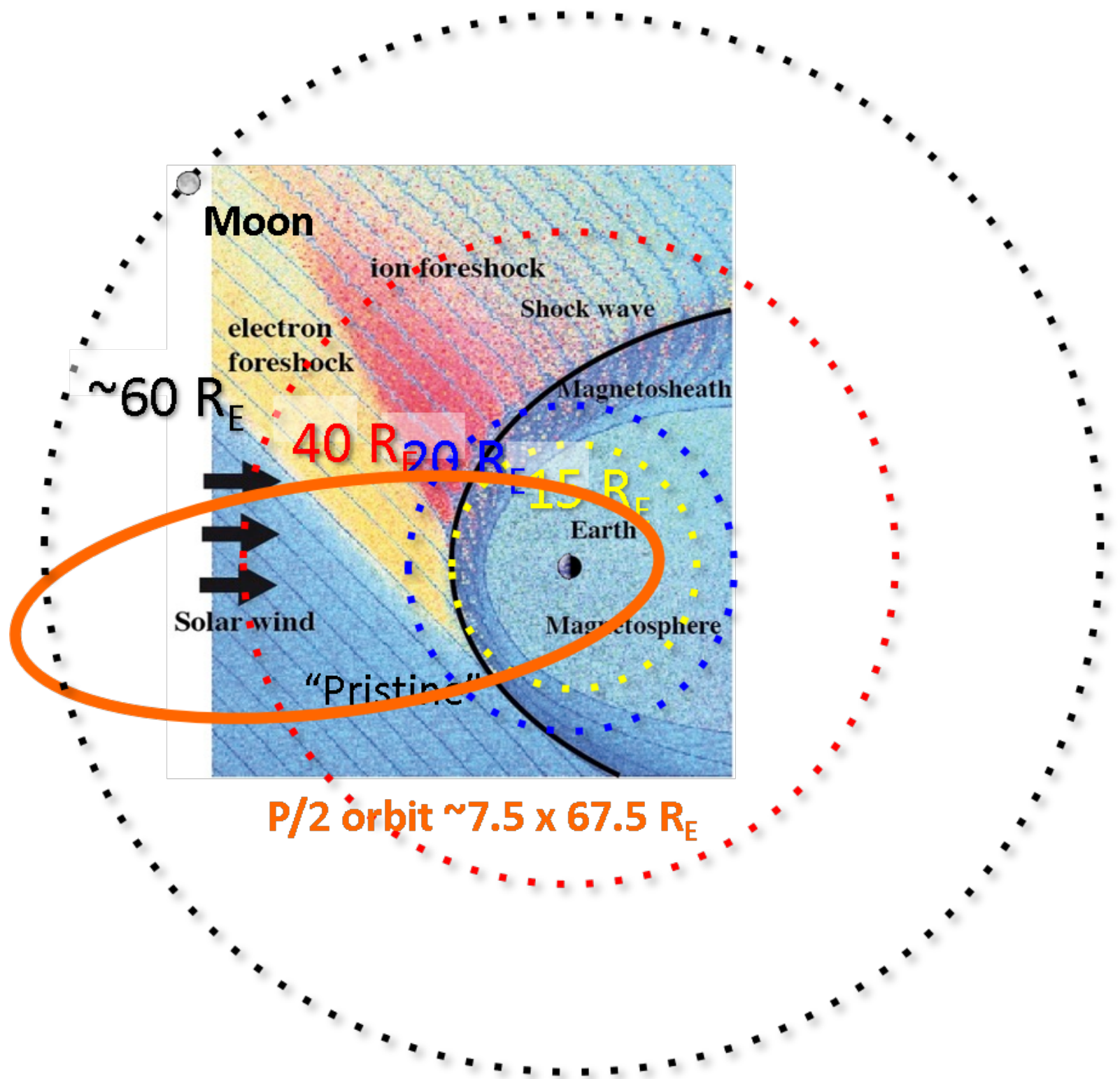

Electrostatic Analyzers (ESA) [LANL & UCB]

- Ion ESA **(LANL)**
  - Energy range: 260 eV to 36 keV
  - Energy resolution: dE/E ~ 5%
- Electron ESA: **(UCB)**
  - 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

MISSION ARCHITECTURE

HelioSwarm ConOps leverages large and small spacecraft capabilities. HelioSwarm is optimized for simultaneously probing multiple spatial scales from ~50 to ~3000 km, exploring all regions of turbulent cascade that connect fluid scale processes with sub-ion scales. The HelioSwarm mission design takes advantage of natural orbital motion so the swarm members disperse at high altitude for science data collection and converge at lower altitudes do crosslink data to the Hub for transmission to the ground. The coordinated Concept of Operations allows approximately 9 days of most advantageous science activity above 40 Re and 5 days when lower altitudes and smaller separations support efficient data transmission. The TESS-like P/2 lunar resonant orbit allows apogee to pass through regions of pristine solar wind, bow shock, foreshock, and magnetotail in the yearly cycle of the Earth's motion around the Sun.

[VIDEO] https://www.youtube.com/embed/3VSUP8GPbKQ?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0
[VIDEO] https://www.youtube.com/embed/3VSUP8GPbKQ?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0
•Swarm orbit : constrained by requirement to sufficiently sample pristine solar wind (>40 RE) "uncontaminated" by electron and ion foreshocks, magnetosheath, and magnetosphere.

•P/2 lunar resonant orbit comprising one "hub" (ESPA ring) and ten co-orbiting "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 line.
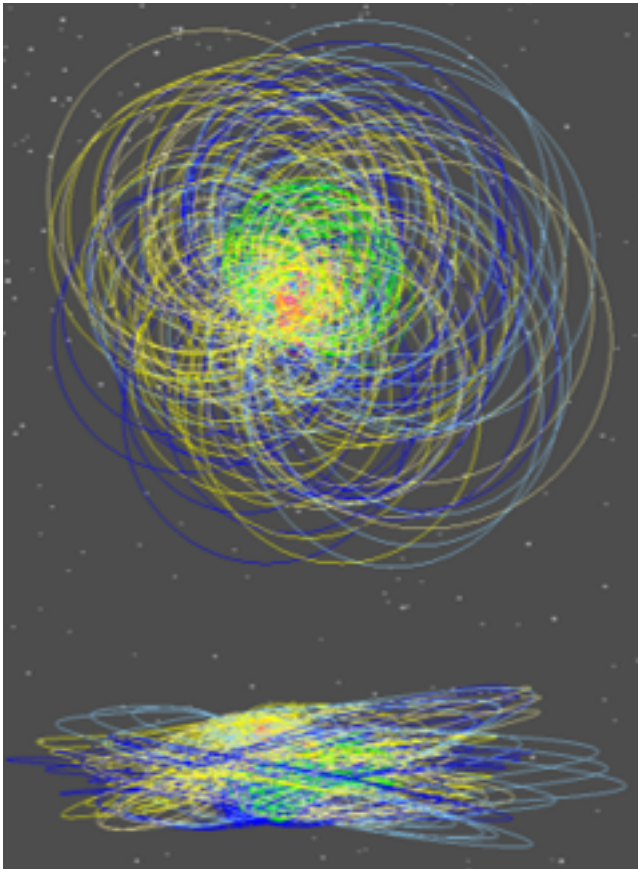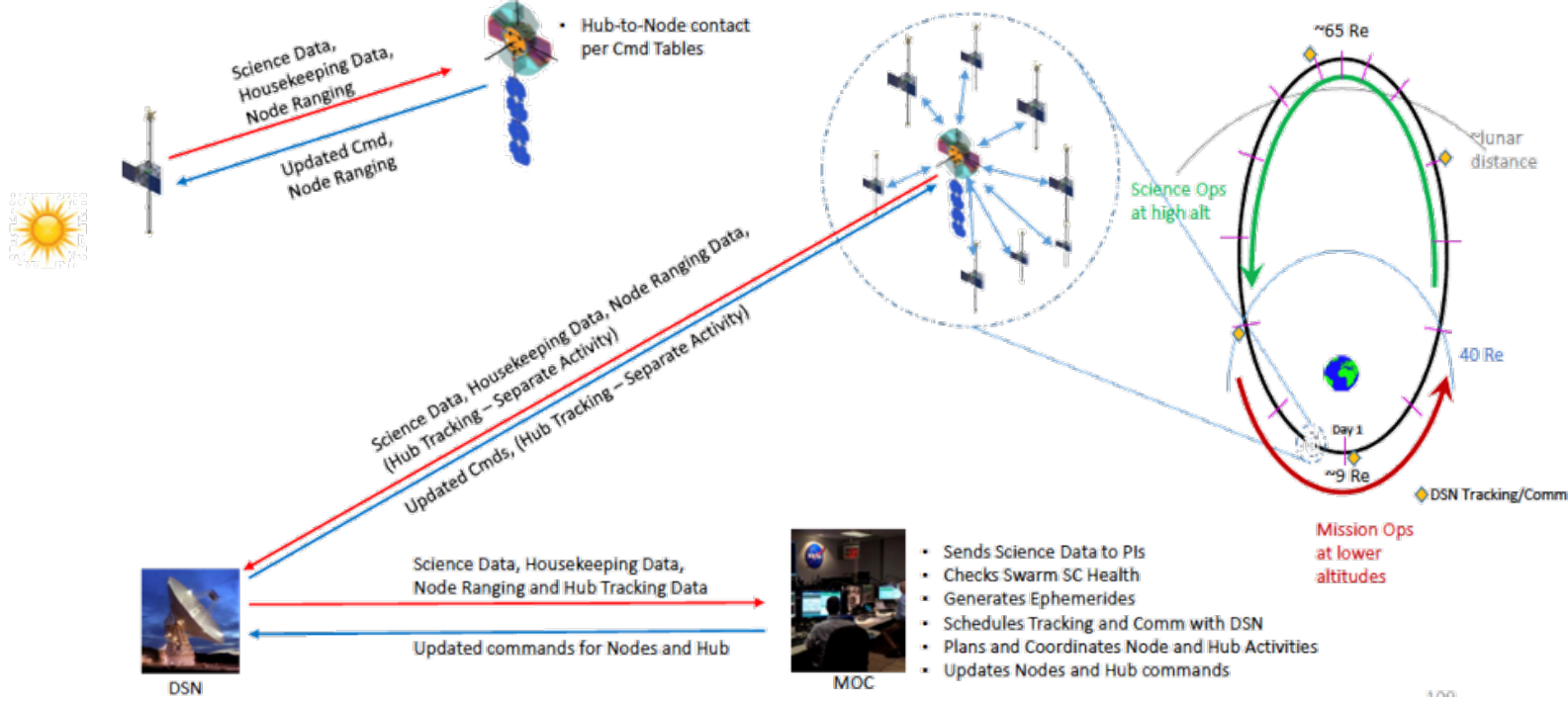

The graph below shows the evolution of spacing between the hub and the nodes over a generic 2-year mission lifetime. The two-week periodicity is an intended consequence of the orbital design: nodes move closer to the hub at perigee to allow for more efficient science data transfers.

Deployment may be optimized to produce specified long-periodic and short-periodic swarm size oscillations.
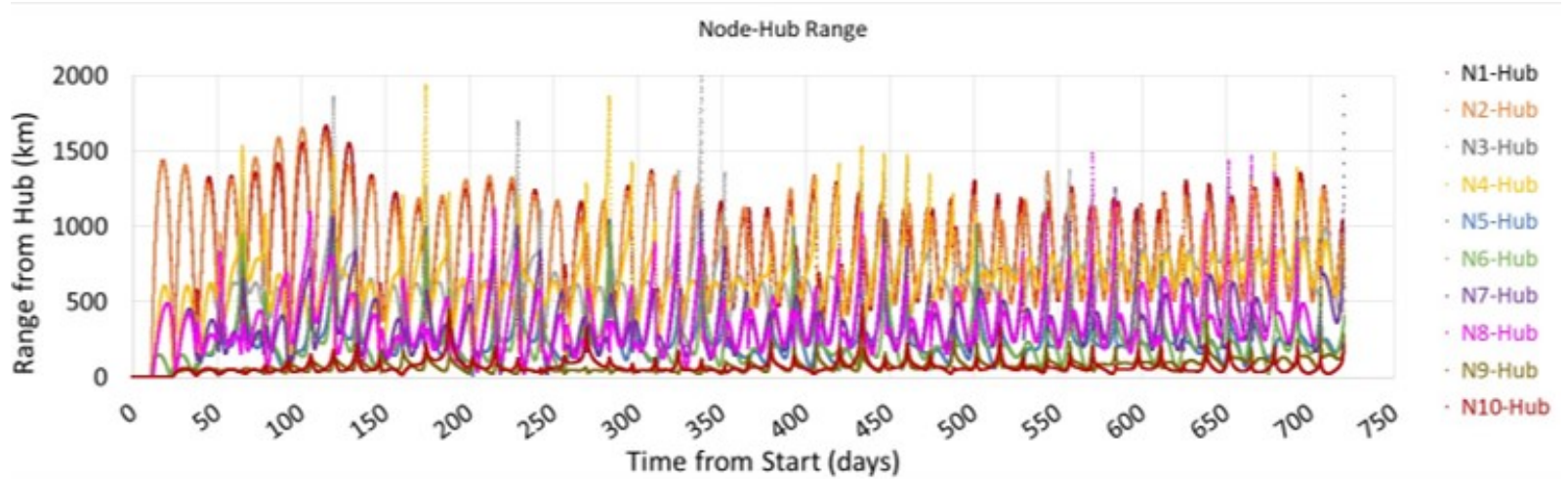
The image below is the operations concept for Helioswarm. A large spacecraft carries the smallsats swarm to their destination orbit, deploys them, and then supplies communications relay functions to Earth; operated as swarm: nodes communicate with hub, hub with ground. Maneuvers occur once per orbit (typically 0.01 – 0.1 m/sec); cumulative delta-V budget over a 2-year mission is <20m/sec.

Science Data,
Housekeeping Data,
Node Ranging

Updated Cmd,
Node Ranging

• Hub-to-Node contact
per Cmd Tables

Science Data, Housekeeping Data, Node Ranging Data,
(Hub Tracking – Separate Activity)

Updated Cmds, (Hub Tracking – Separate Activity)

Science Data, Housekeeping Data,
Node Ranging and Hub Tracking Data

Updated commands for Nodes and Hub

DSN

MOC

• Sends Science Data to PIs
• Checks Swarm SC Health
• Generates Ephemerides
• Schedules Tracking and Comm with DSN
• Plans and Coordinates Node and Hub Activities
• Updates Nodes and Hub commands

~65 Re

~lunar
distance

Science Ops
at high alt

40 Re

Day 1

~9 Re

◆ DSN Tracking/Comm

Mission Ops
at lower
altitudes

MISSION SUITABILITY II

The movies below show the evolution of the swarm geometry on an hourly basis over the mission lifetime for two different orbital inclinations: 21° (upper movie) and 45° (lower movie).

[VIDEO] https://www.youtube.com/embed/jY6B8niAjZc?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0
[VIDEO] https://www.youtube.com/embed/jY6B8niAjZc?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0

[VIDEO] https://www.youtube.com/embed/OmjeRrmNExQ?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0
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In the movies are shown the location of the nodes compared to the hub in xyz GSE coordinates. Also shown are the elongation, planarity, and length scales of the constituent tetrahedra, the parallel and perpendicular projections of the interspacecraft baselines with respect to the Parker magnetic field, and a simplified rendition of the baseline distribution highlighting the broad coverage of the swarm.

ABSTRACT

Turbulence plays a critical role in controlling the physics of the collisionless, magnetized plasmas that pervade our solar system as well as astrophysical systems throughout the cosmos. The pristine solar wind near Earth offers a natural laboratory for the in situ observation of turbulent fields and particle distributions that are representative of those throughout the universe. Understanding the transport of mass, momentum, and energy, and associated dissipation in such systems is important and compelling, but its exact nature remains a mystery owing primarily to our past, present, and planned future approaches to reveal it. To date, all in situ observations of solar wind plasmas have single point measurements (i.e., ACE, WIND), or have focused on a single scale through the use of carefully controlled clusters of four spacecraft (i.e., Cluster, MMS). Turbulence is fundamentally a multi-scale, three-dimensional, time-evolving phenomenon and therefore neither single point measurements nor even a cluster of four spacecraft provide insight into the full nature of the turbulent medium. To reveal the full temporal and spatial structure of turbulence requires observations at an array of points that far exceeds the tetrahedral configurations flown to date. With the advent of low resource sensors and small satellites, such arrays of spacecraft are now possible and promise to transform our knowledge of turbulence. Rather than flying in formation, a swarm of small spacecraft (nodes) will enable direct measurement of a wide range of spatial and temporal scales that span physical ranges of interest. In this presentation, we describe a newly-feasible, innovate mission concept employing such a swarm of many small spacecraft. The cost-effective mission will reveal and quantify key unknown aspects of turbulence, allowing us to understand the cascade of energy from longer scale and time sizes toward and into smaller scales and shorter times.