HELIO SWARM

THE NATURE OF TURBULENCE IN SPACE PLASMAS

Mission Design & Operations Approach for the HelioSwarm Mission

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HELIO SWARM

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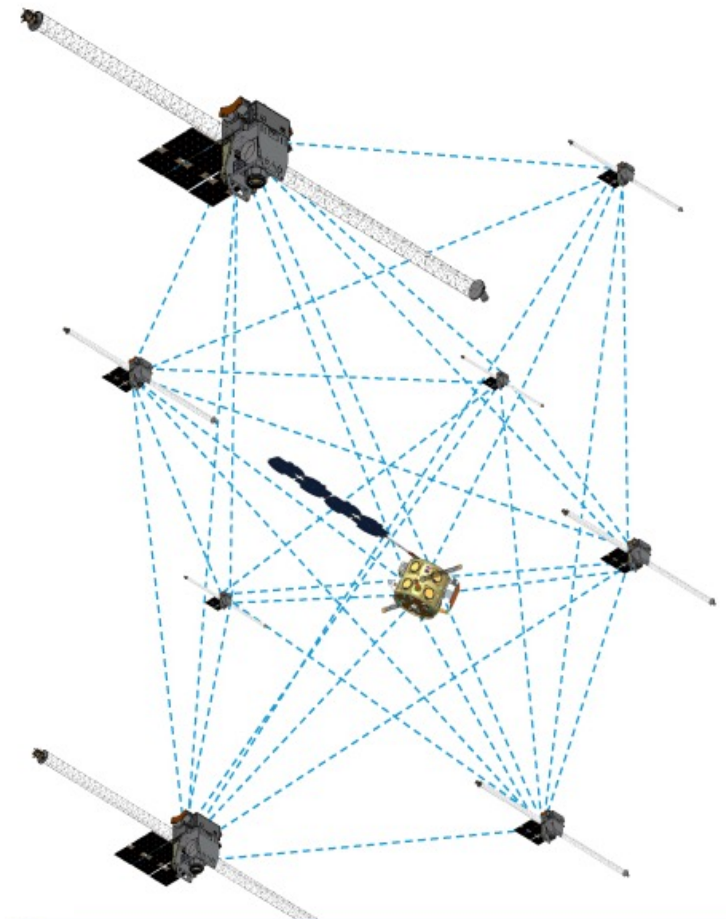
Agenda

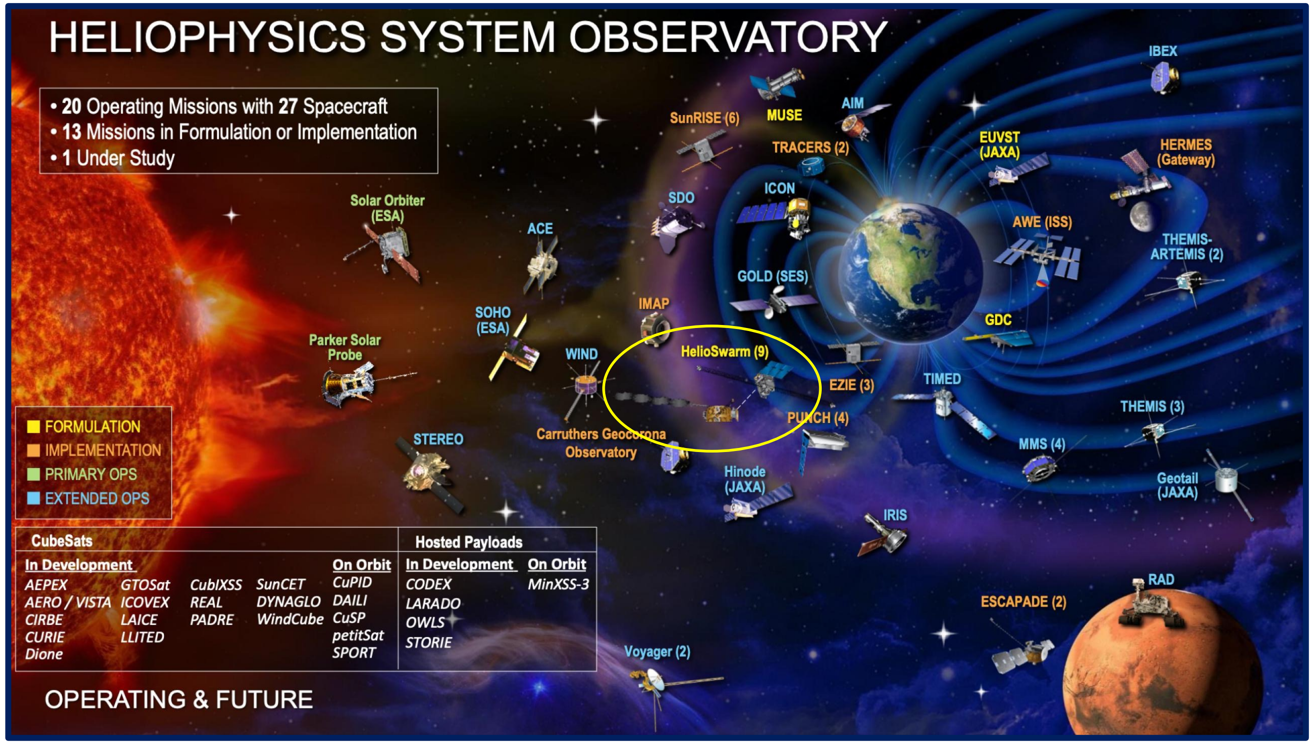


- **HelioSwarm Introduction**
- **Mission Concept**
  - **Science Investigation**
  - **Spacecraft and Instruments**
  - **Orbit Dynamics**
- **Concept of Operations Highlights**
- **Mission Operations & Ground Systems Overview and Approach**
- **Questions & Discussion**

Basic Mission Information

- NASA Science Mission Directorate (SMD) Explorers Program competed mission
- Heliophysics Medium-Sized Explorer class mission (aka “MIDEX”)
- Timeline:

Milestone	Current Date
Step-1 Proposal	Sep. 2019 (complete)
Step-2 Proposal	Jul. 2021 (complete)
Selection	Feb. 2022 (complete)
Phase B Start	May 2024
PDR	Sep. 2025
CDR	Nov. 2026
Launch	Jan. 2029
Operations	6 mo. Early Ops / Comm. 12 mo. Science

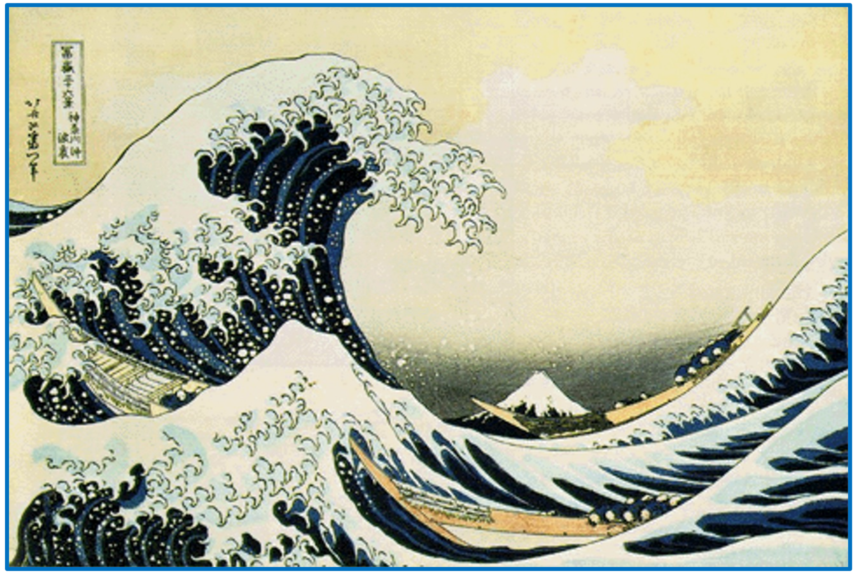


Source: https://science.nasa.gov/heliophysics/mission-fleet-diagram

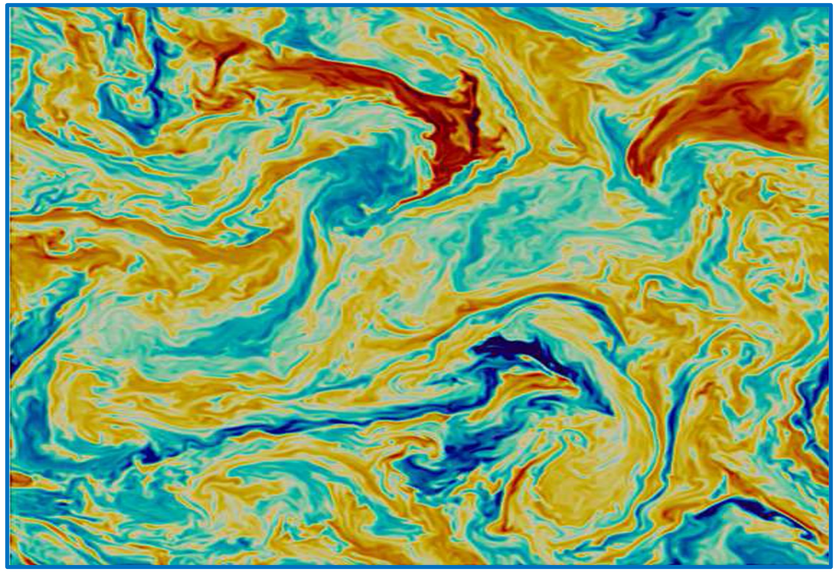
Mission Concept

The Nature of Turbulence

- Turbulent flow is one in which a gas, liquid, or <u>plasma</u> undergoes irregular fluctuations and mixing
- One of the three fundamental plasma physics processes … but the least understood



Katsushika Hokusai, *The Great Wave Off Kanagawa,* 1831 (Thirty-six Views of Mt. Fuji series)

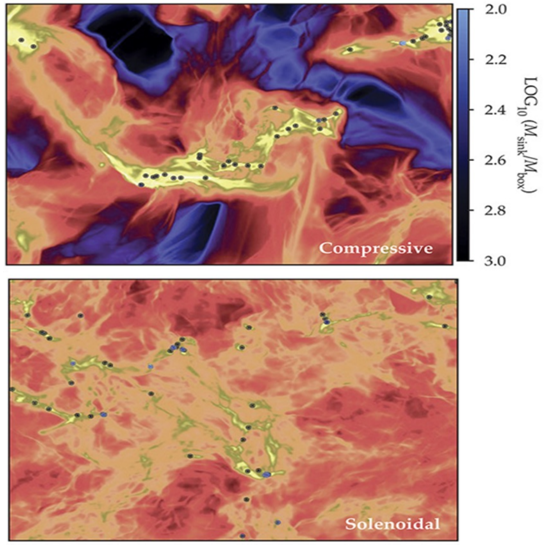


Meyrand et al 2019

Multipoint cross-scale measurements of the plasma physics are needed to resolve which theories are correct.

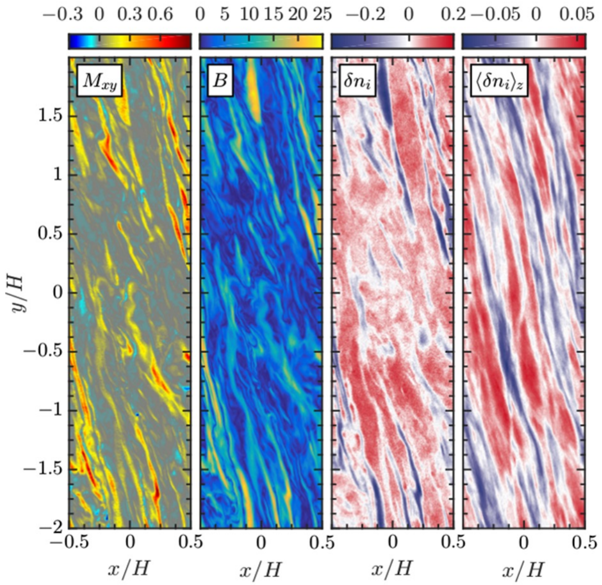
A Universal Phenomenon

Star Formation



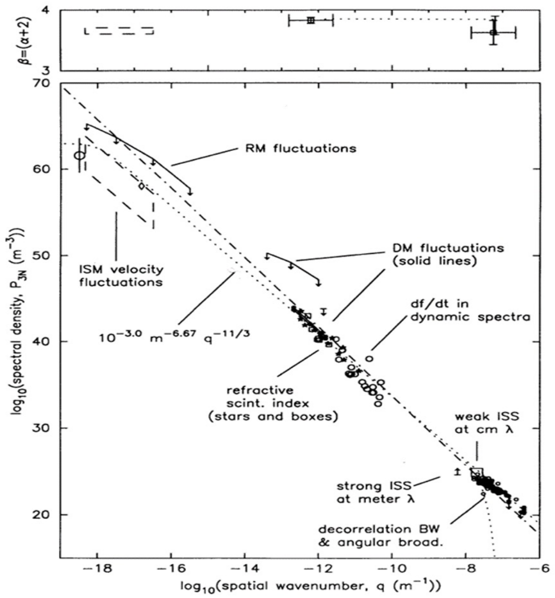
Star Formation Simulations
(Federrath & Klessen 2012)

Black Hole Accretion Disks



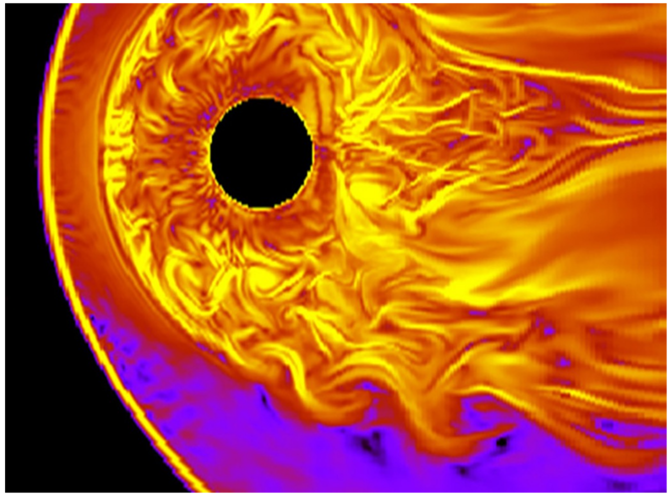
MRI Turbulence Simulations
(Kunz et al 2016)

Interstellar Medium (ISM)



ISM Observations
(Armstrong et al 1995)

Solar Wind / Earth's Magnetosphere



OpenGGCM MHD simulation of Earth's magnetosphere
(S. Kavosi, J. Raeder et al 2015)

Turbulence plays a fundamental role in plasmas throughout the universe.

The Ideal Laboratory

The solar wind and its interaction with Earth's magnetosphere provide an ideal laboratory for the study of space plasma turbulence.

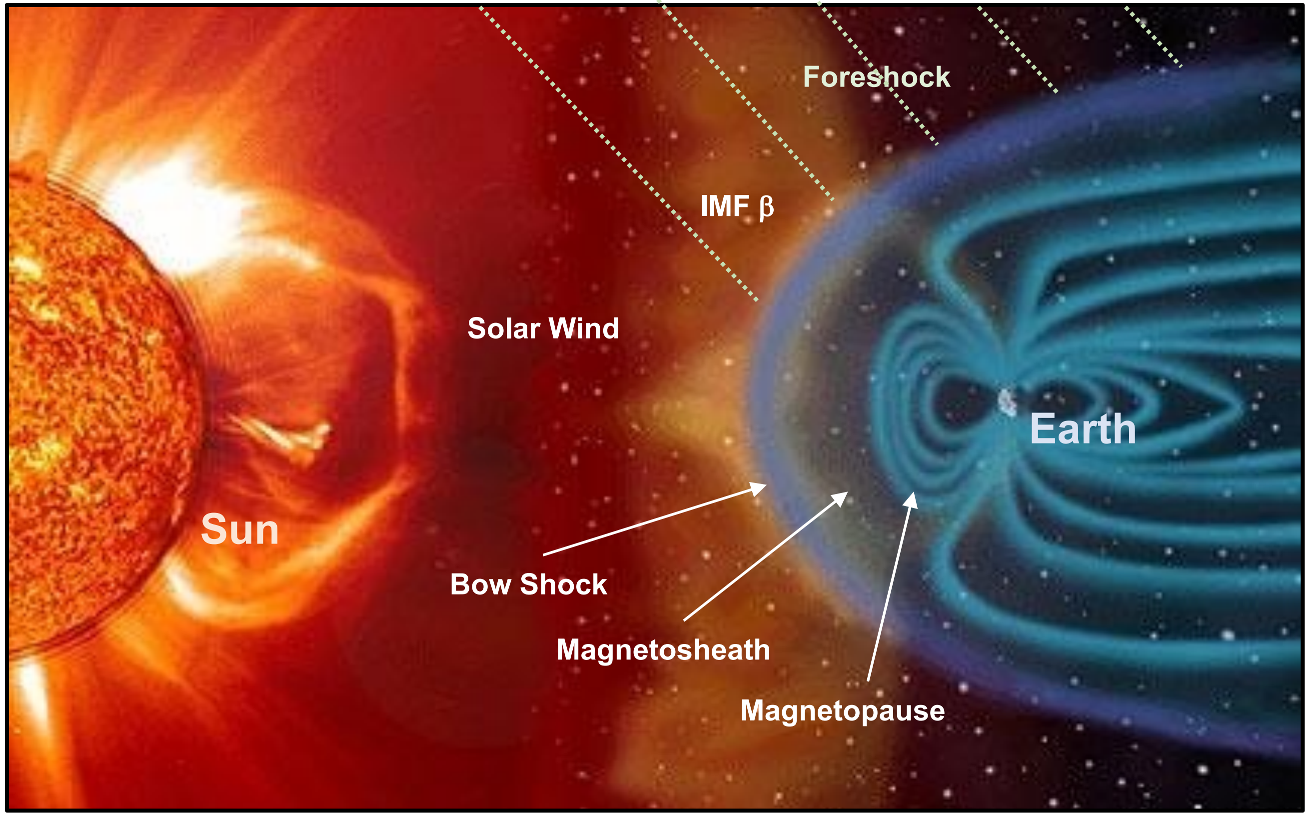
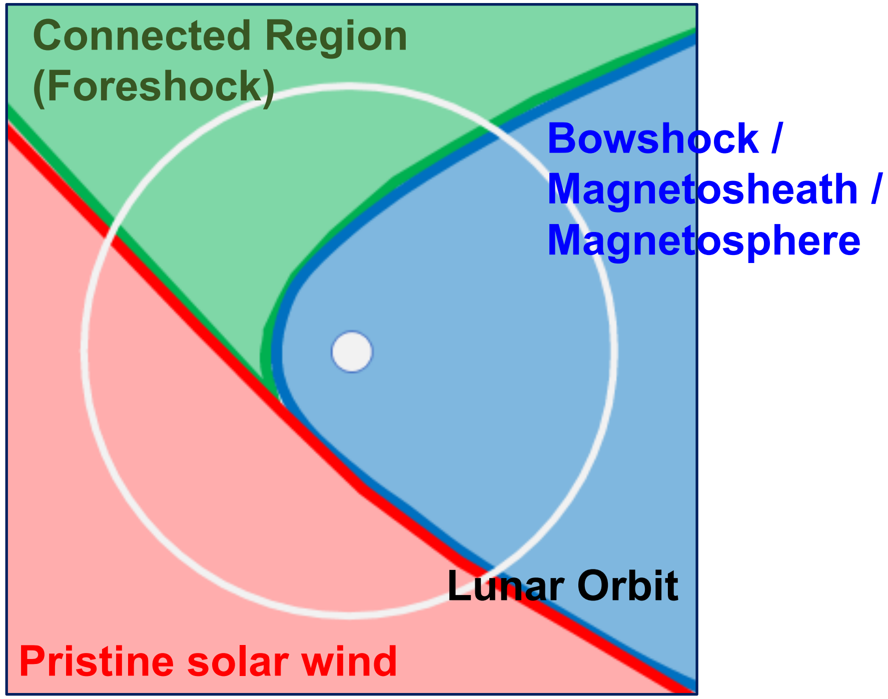


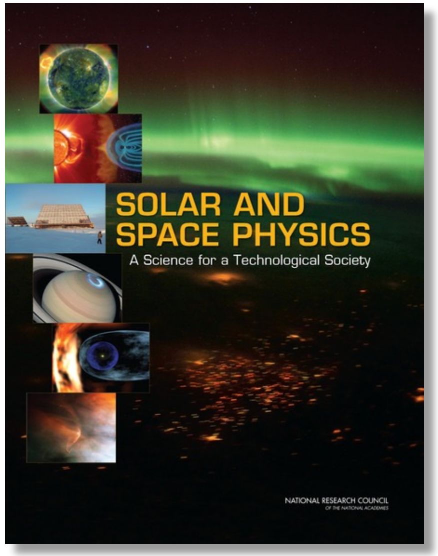
Image Credit: NASA/ESA



HelioSwarm's regions of interest

Science Investigation Goals and Approach

National Academy of Sciences 2013 Decadal Survey



"… understand the origins and effects of turbulence"

"… a multi-spacecraft mission to address cross-scale plasma physics"

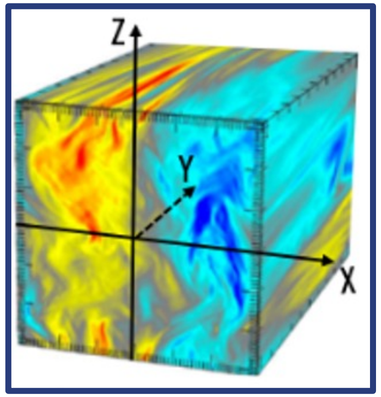
HelioSwarm Science Investigation Goals

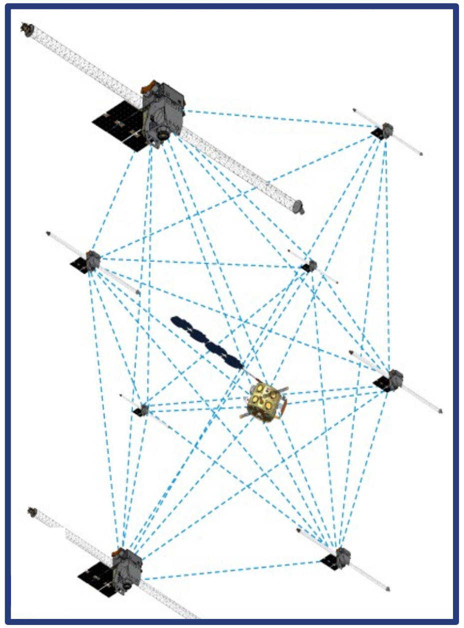
Goal #1:
Reveal the 3D spatial structure and dynamics of turbulence in a weakly collisional plasma.

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

HelioSwarm Science Investigation Approach

Novel use of a 9-S/C swarm to make simultaneous multi-point cross-scale measurements within near-Earth plasma environments.





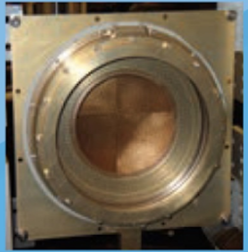
Instrument Suite Overview

HUB & NODE

Fluxgate Magnetometer (MAG)
- Vector DC magnetic fields
- Solar Orbiter post-environmental heritage and JUICE design heritage

Search Coil Magnetometer (SCM)
- Vector AC magnetic fields
- JUICE design heritage

Faraday Cup (FC)
- Solar wind plasma density and velocity
- Parker Solar Probe, WIND, DSCOVR flight heritage



HUB ONLY

Ion Electrostatic Analyzer (iESA)
- Ion velocity distributions
- Solar Orbiter post-environmental heritage and MAVEN flight heritage

Imperial College London (UK)

Laboratoire de Physique des Plasmas (LPP) (France)

Smithsonian Astrophysical Observatory (USA)

Research Institute in Astrophysics and Planetology (IRAP) (France)

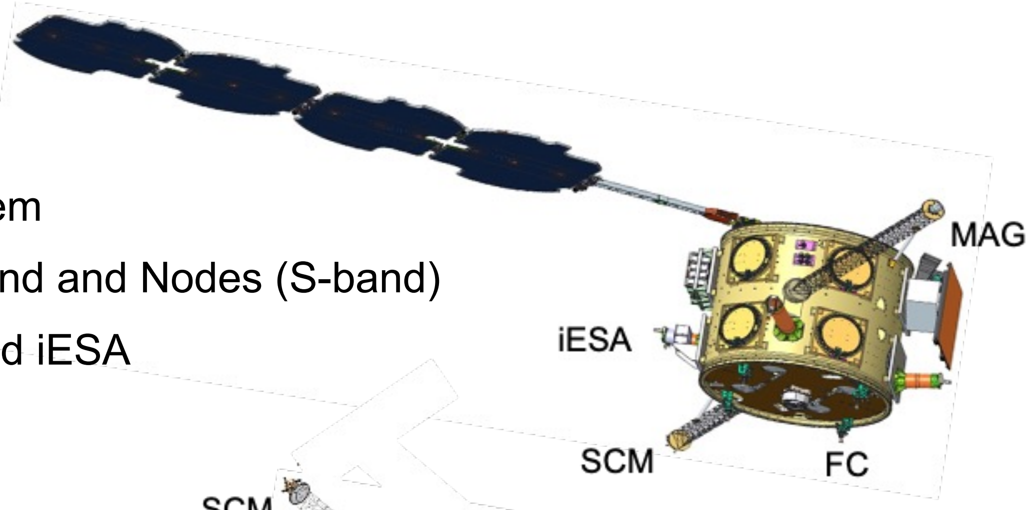
All selected instruments operate simultaneously and nearly continuously resulting in a simple operational concept.

An Electron ESA (eESA), lead by Phyllis Whittlesey (UC Berkeley), is included as a Student Collaboration Option for installation on the Hub

Spacecraft Overview

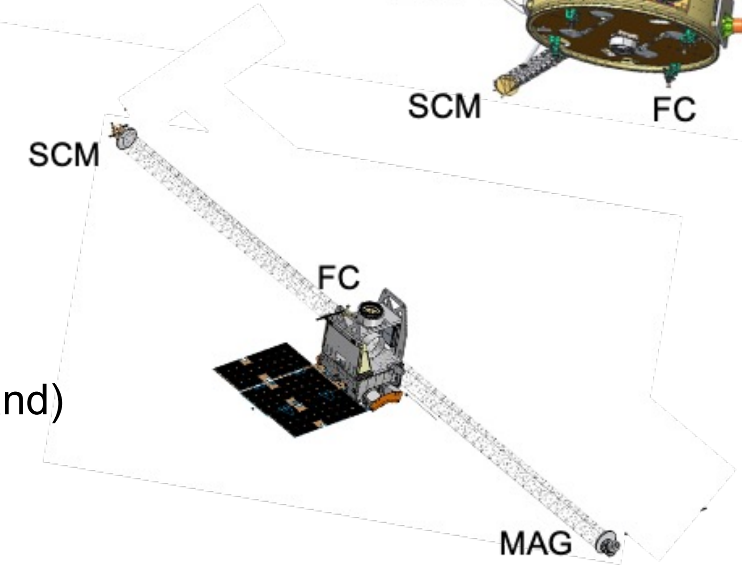
Hub Spacecraft (x1):

- Northrop Grumman
- ESPAStar Product Line
- Hydrazine propulsion system
- Communications with ground and Nodes (S-band)
- Carries SCM, MAG, FC and iESA



Node Spacecraft (x8):

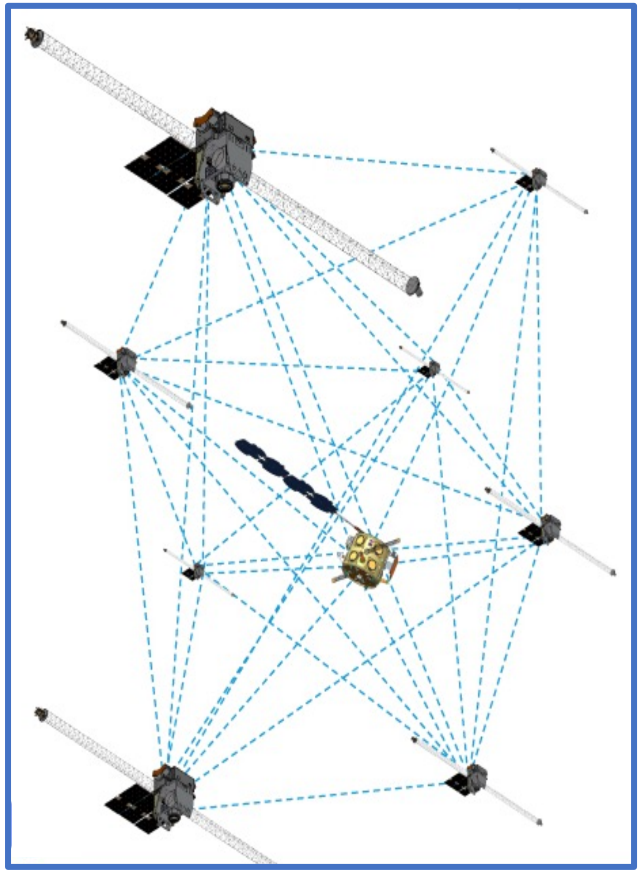
- Blue Canyon Technologies
- Venus Bus Product Line
- Low-thrust ion propulsion system
- Communication with Hub only (S-band)
- Carries SCM, MAG and FC



NOTE: Figures not to scale

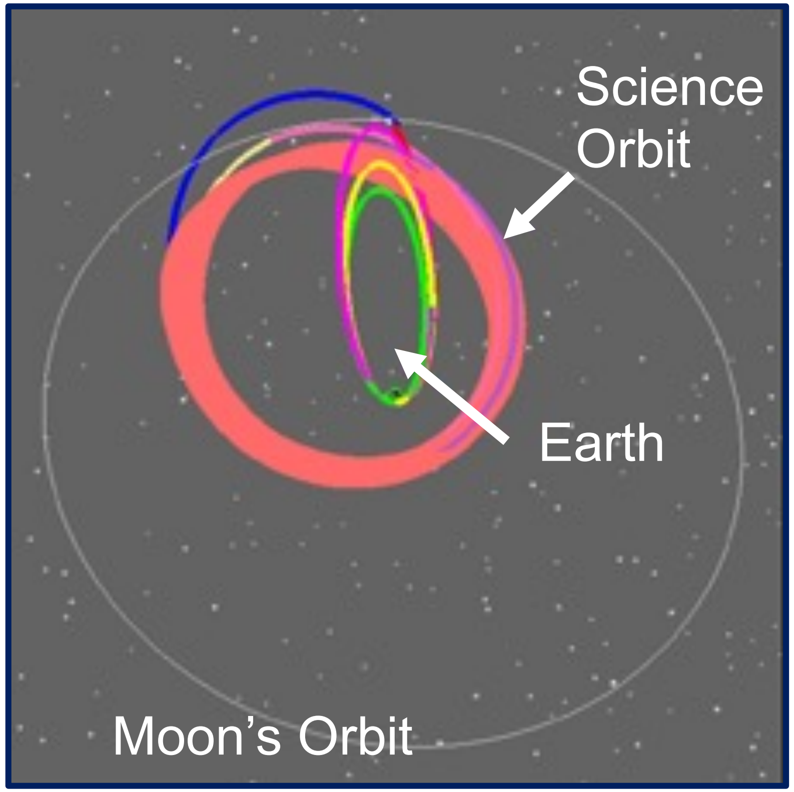
HelioSwarm Observatory:

28 Instruments across 9 spacecraft



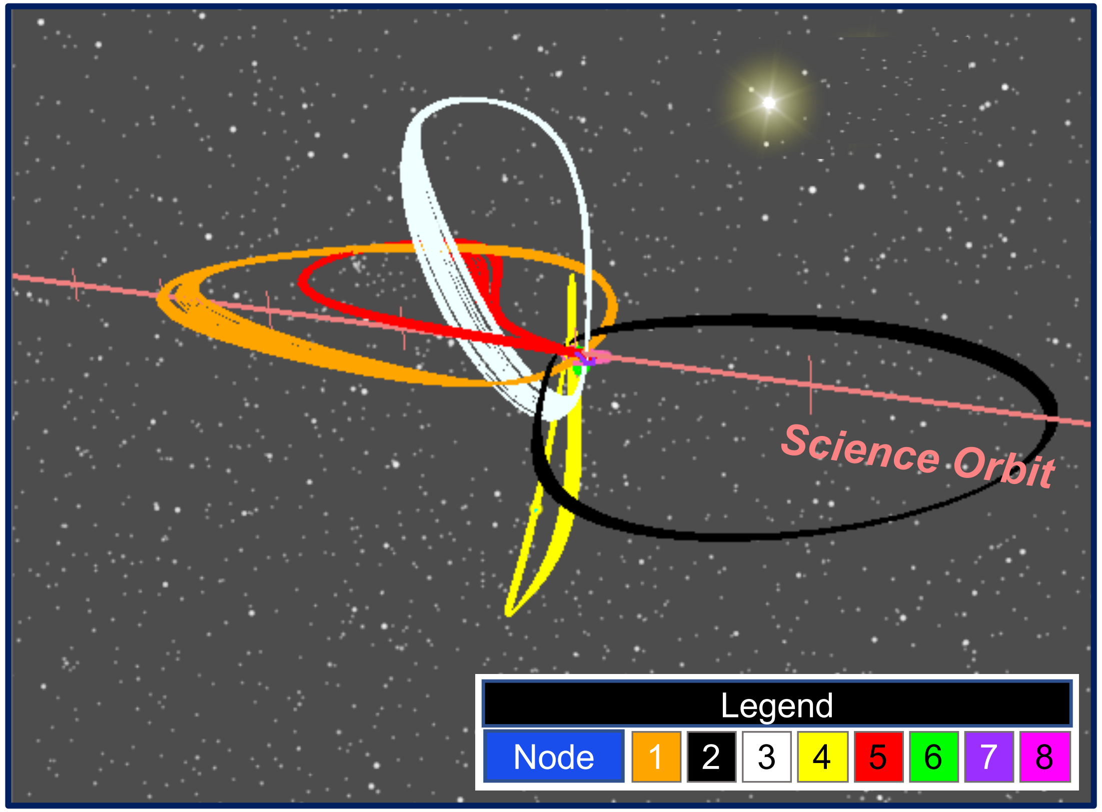
HelioSwarm Orbit Dynamics

HelioSwarm's characterization of plasma turbulence relies on two major orbital design efforts.



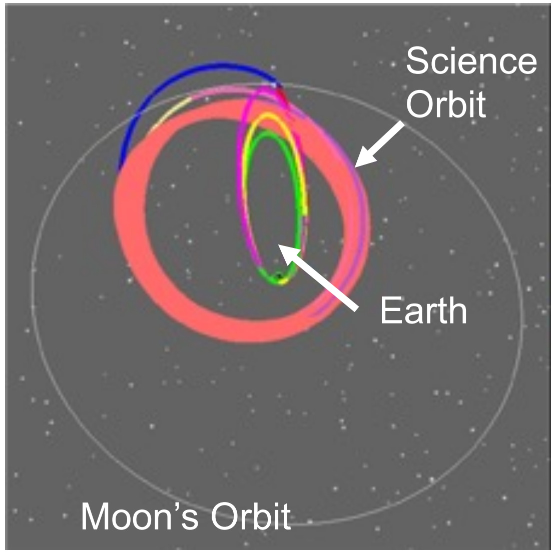
Science Orbit Design / Bulk Motion

Relative Orbit Design / Swarm Motion

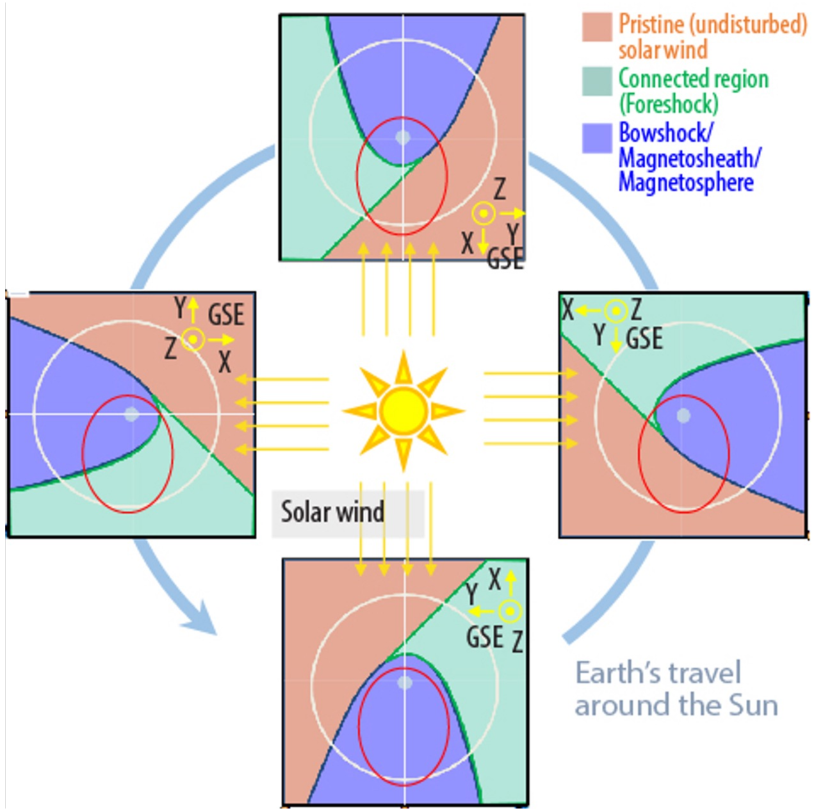


Science Orbit / Bulk Motion

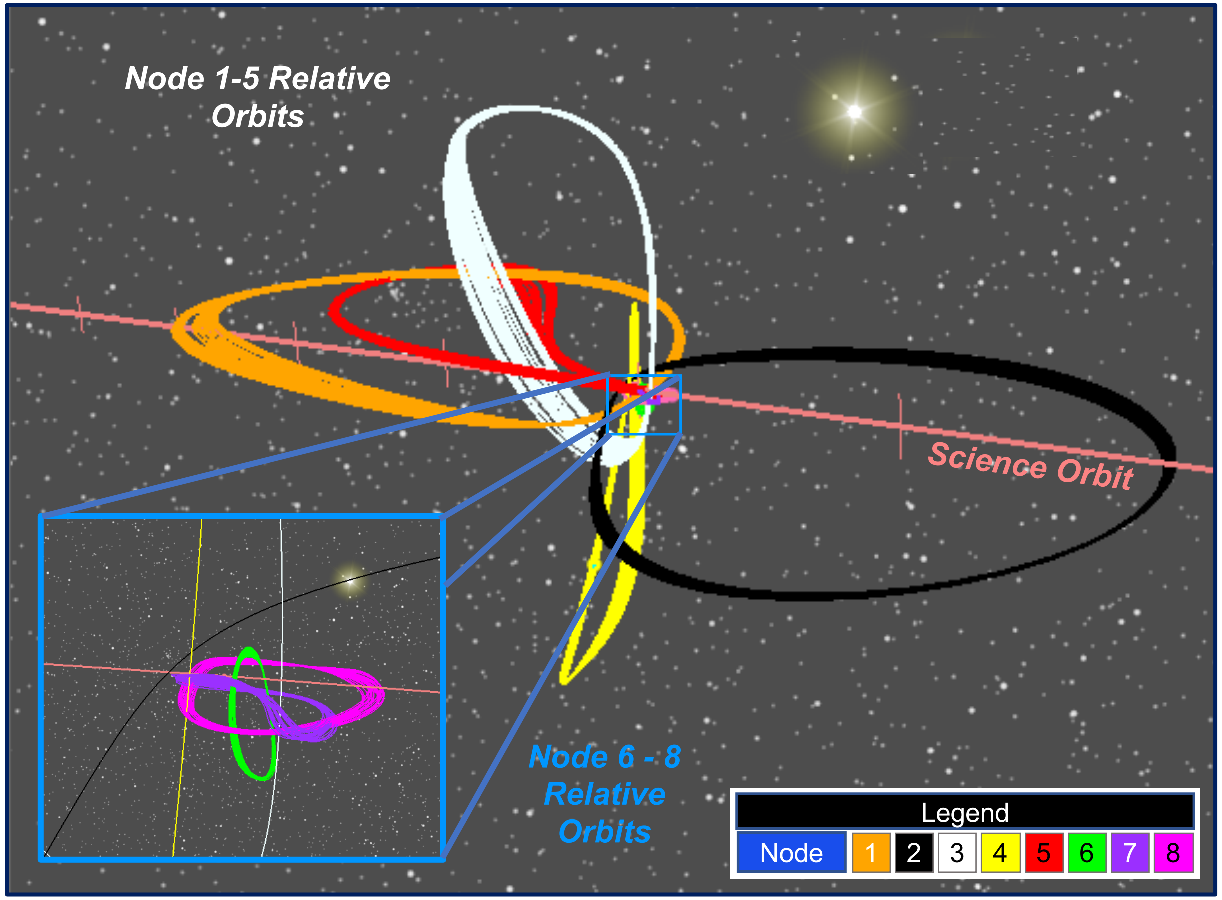
- High-altitude Earth Orbit (HEO)
  - Perigee: 10 - 15 R_E
  - Apogee: 60 - 65 R_E
  - 15-degree inclination
- P/2 Lunar Resonant (~14-day period)
- No maintenance required once established



- Inertially fixed orbit; orientation of orbit relative to Sun-Earth geometric slowly rotates over 12-month science phase

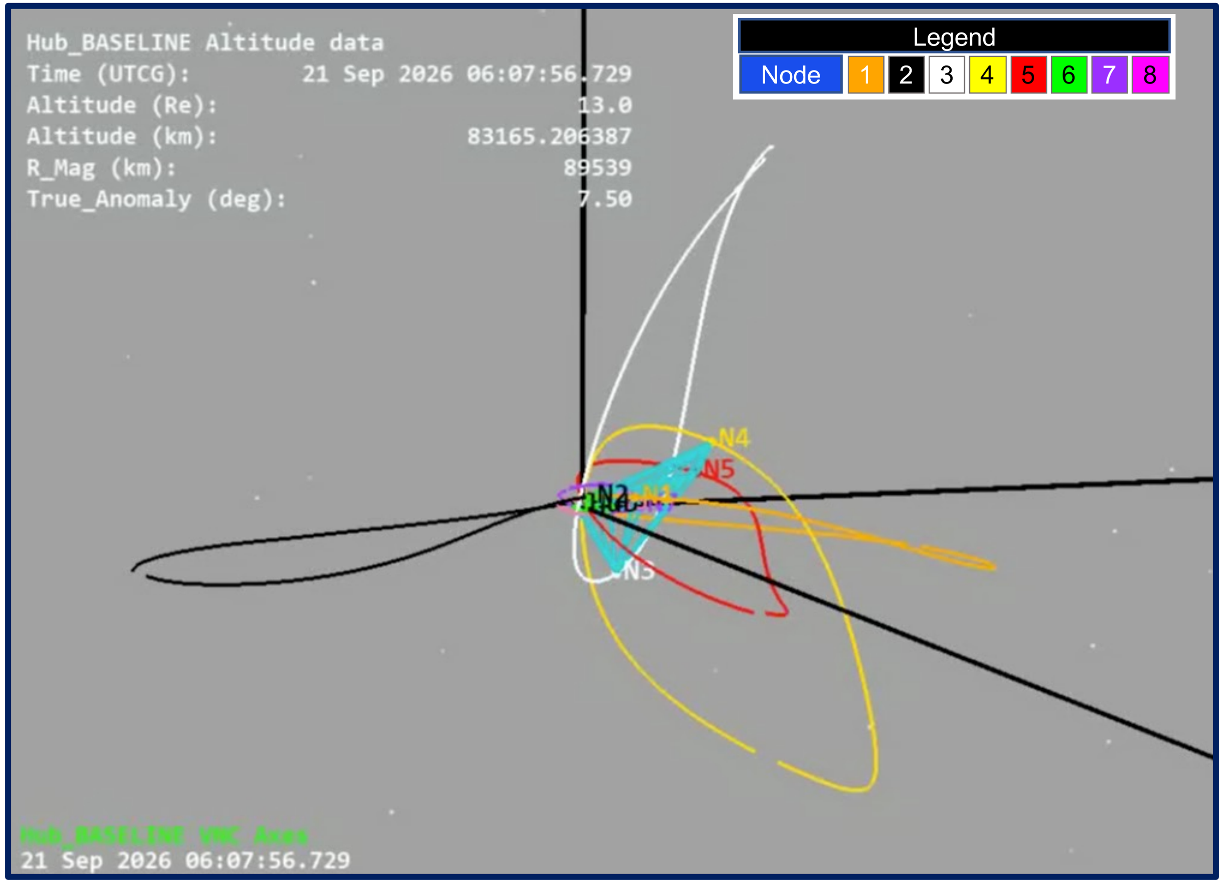


Relative Orbits / Swarm Motion



- Targeted relative orbital motion of the 9 spacecraft creates spatial configurations for observation:
  - “3D Baseline”
  - “Tetrahedra”
- Period of all relative orbits matches the period of the science orbit (~14 days)
- Swarm naturally expands at apogee and contracts at perigee
- Node maneuvers required to maintain the observation geometries
  - 2 Orbit Trim Maneuvers (OTMs) per Node per Orbit

Relative Orbits / Swarm Motion



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Observatory in Relative Scale

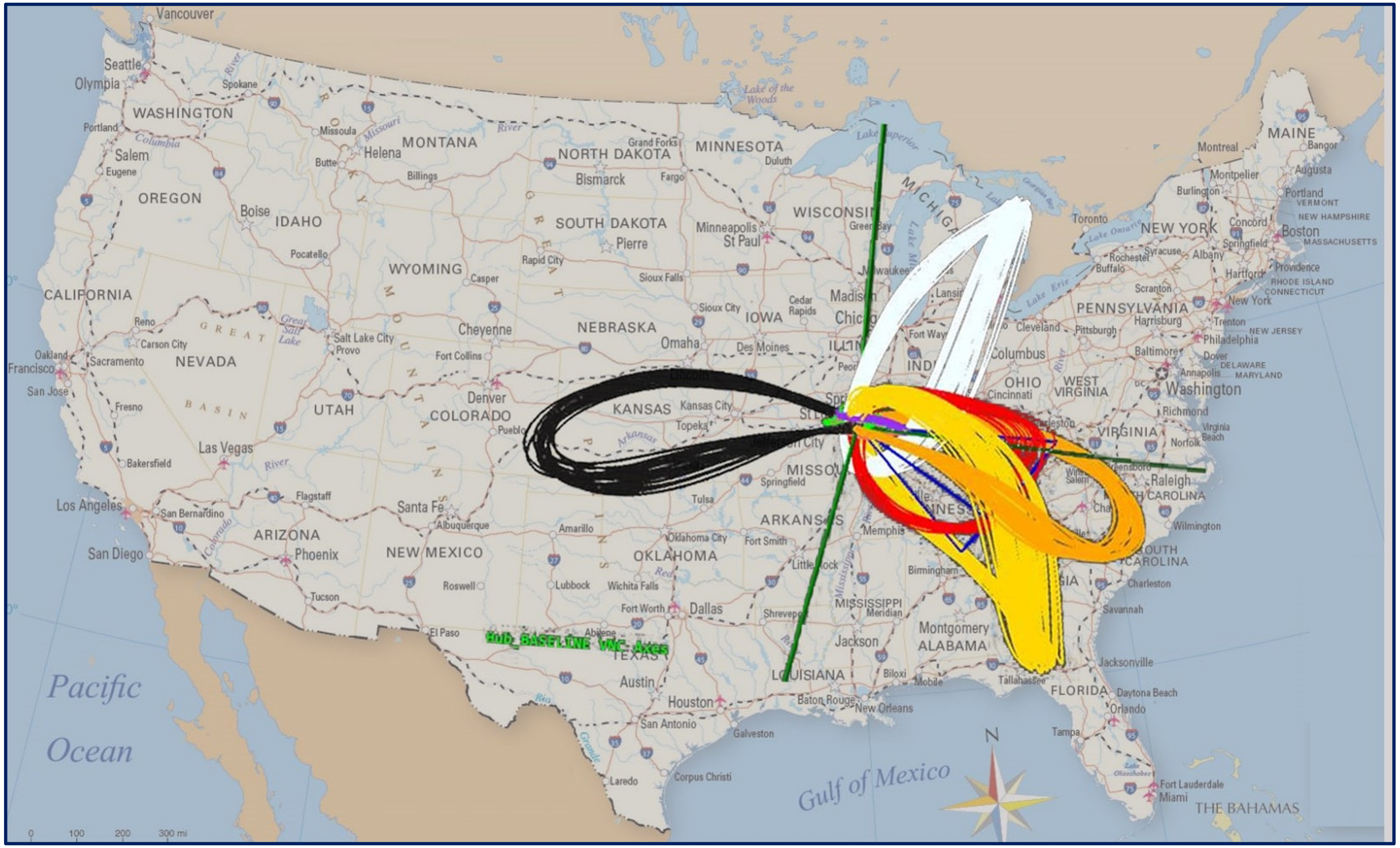
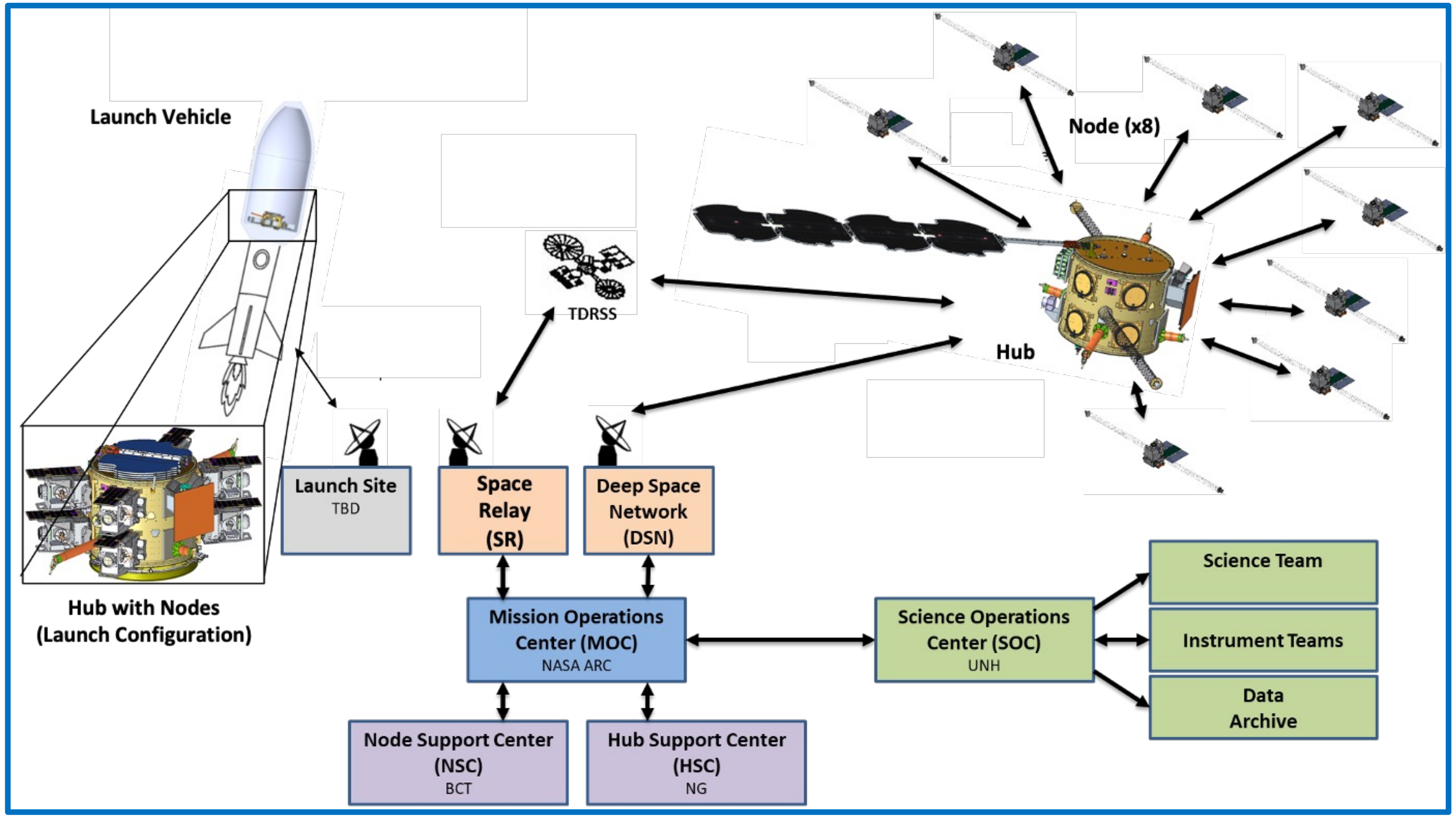


Image Credit: One World – Nations Online project

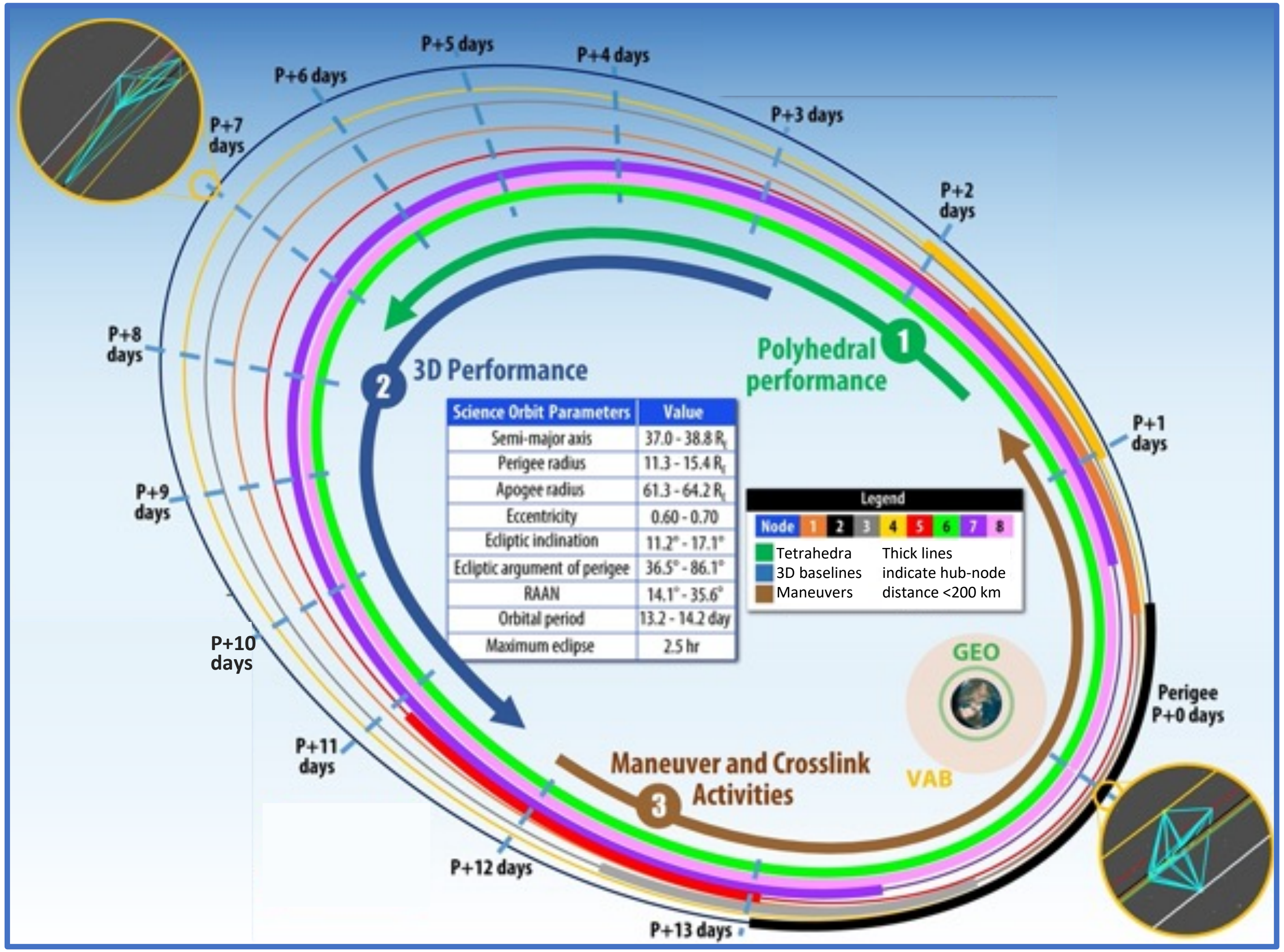
Concept of Operations Highlights

Mission Architecture



- HelioSwarm "flight system" consists of Hub with Nodes attached
- Hub propulsion system used to maneuver into science orbit (via phasing loops and lunar gravity assist)
- Nodes separate in pairs once in science orbit
- All communication with and through the Hub
- Deep Space Network provides majority of ground communication.
- Mission Operations at NASA ARC, Science Operations at Univ. of New Hampshire

Science Phase Overview

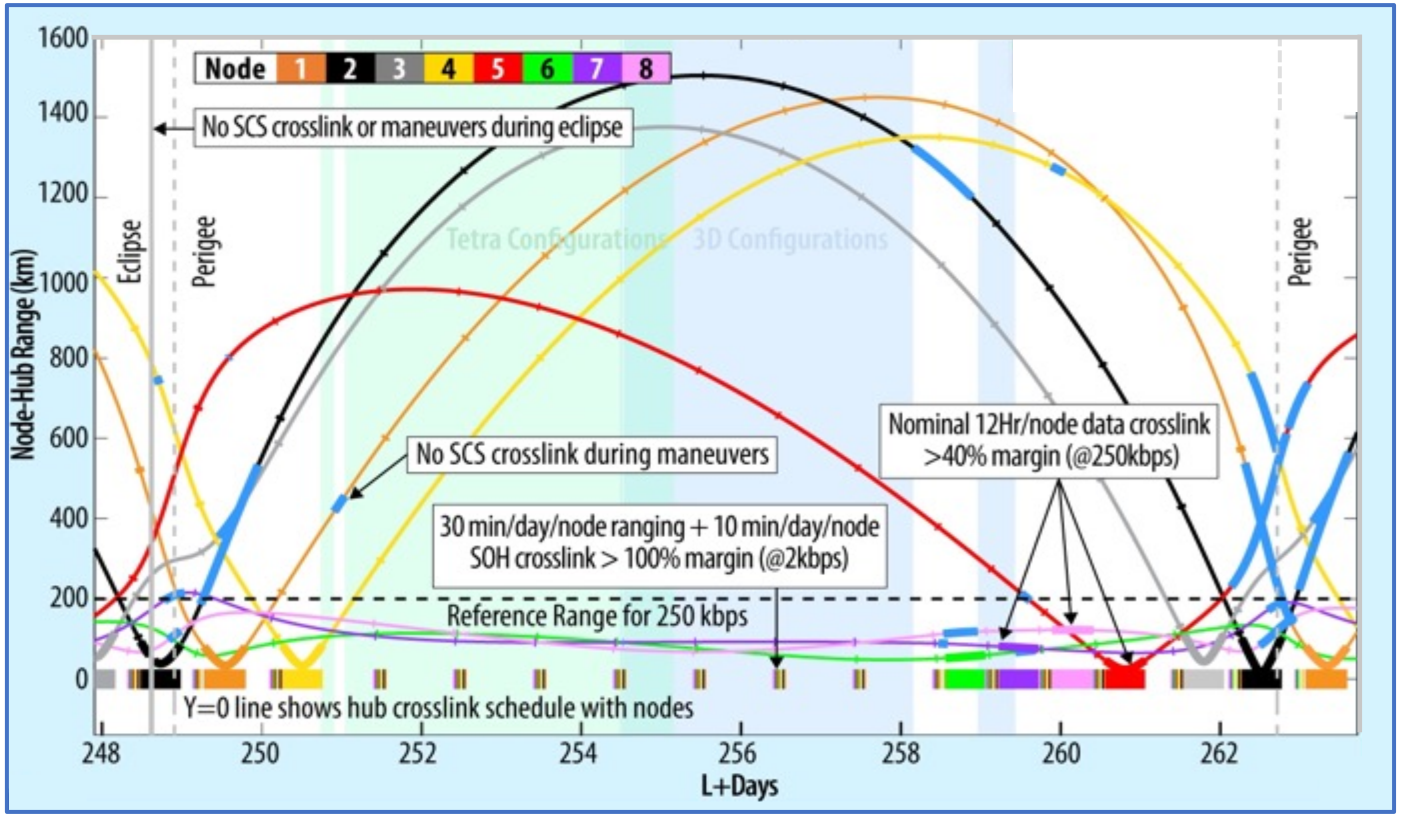


Science Orbit Parameters	Value
Semi-major axis	37.0 - 38.8 R_E
Perigee radius	11.3 - 15.4 R_E
Apogee radius	61.3 - 64.2 R_E
Eccentricity	0.60 - 0.70
Ecliptic inclination	11.2° - 17.1°
Ecliptic argument of perigee	36.5° - 86.1°
RAAN	14.1° - 35.6°
Orbital period	13.2 - 14.2 day
Maximum eclipse	2.5 hr

Near Perigee	Away from Perigee
Swarm moving faster	Swarm moving slower
Swarm contracts	Swarm expands
Less valuable science	Most valuable science
Emphasis on communications & maneuvers: • Crosslink • Ground comms.	Emphasis on science observations: • Polyhedral/tetrahdra • “3D baselines”

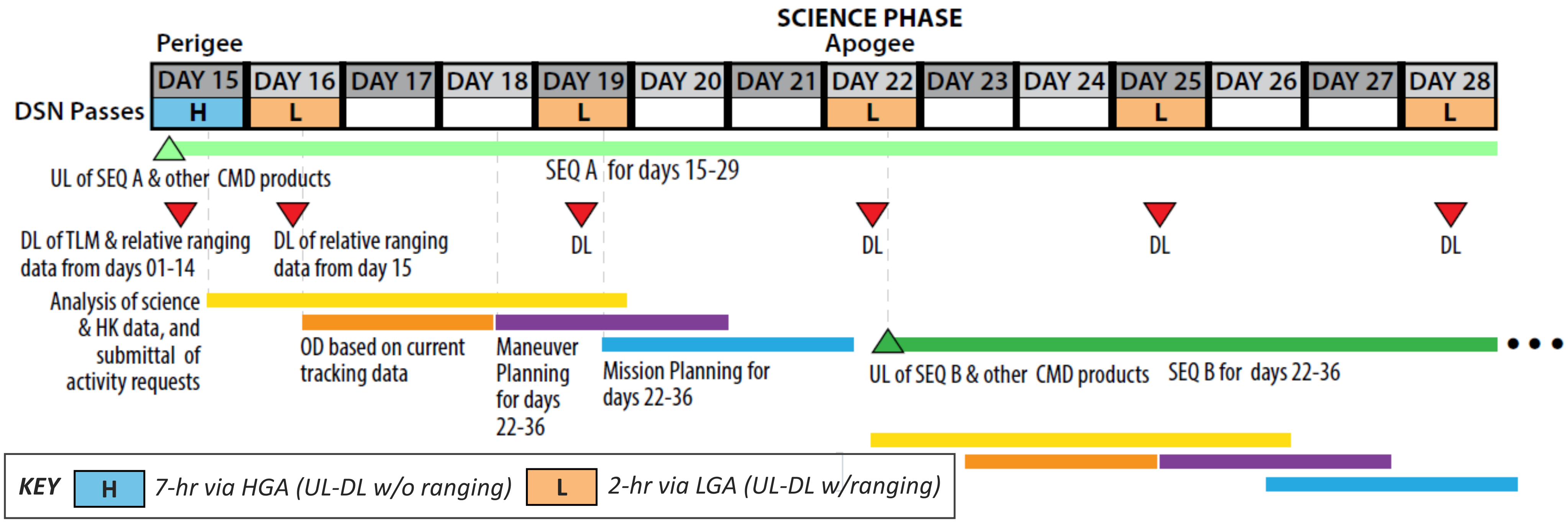
Highly repetitive science phase operational concept simplifies operations

Science Phase Communications



- High-rate Node-to-Hub data downlinks occur once per orbit near perigee
  - 12 hr / node
- Individual relative orbits are phased to provide separation between Node closest approaches
  - Revisit pattern repeats each orbit
- Daily Node-to-Hub SOH and relative ranging
- Node-to-Hub contacts are driven by command sequence on the hub
- Node maneuvers are deconflicted with communication activities

Science Phase Operations Timeline



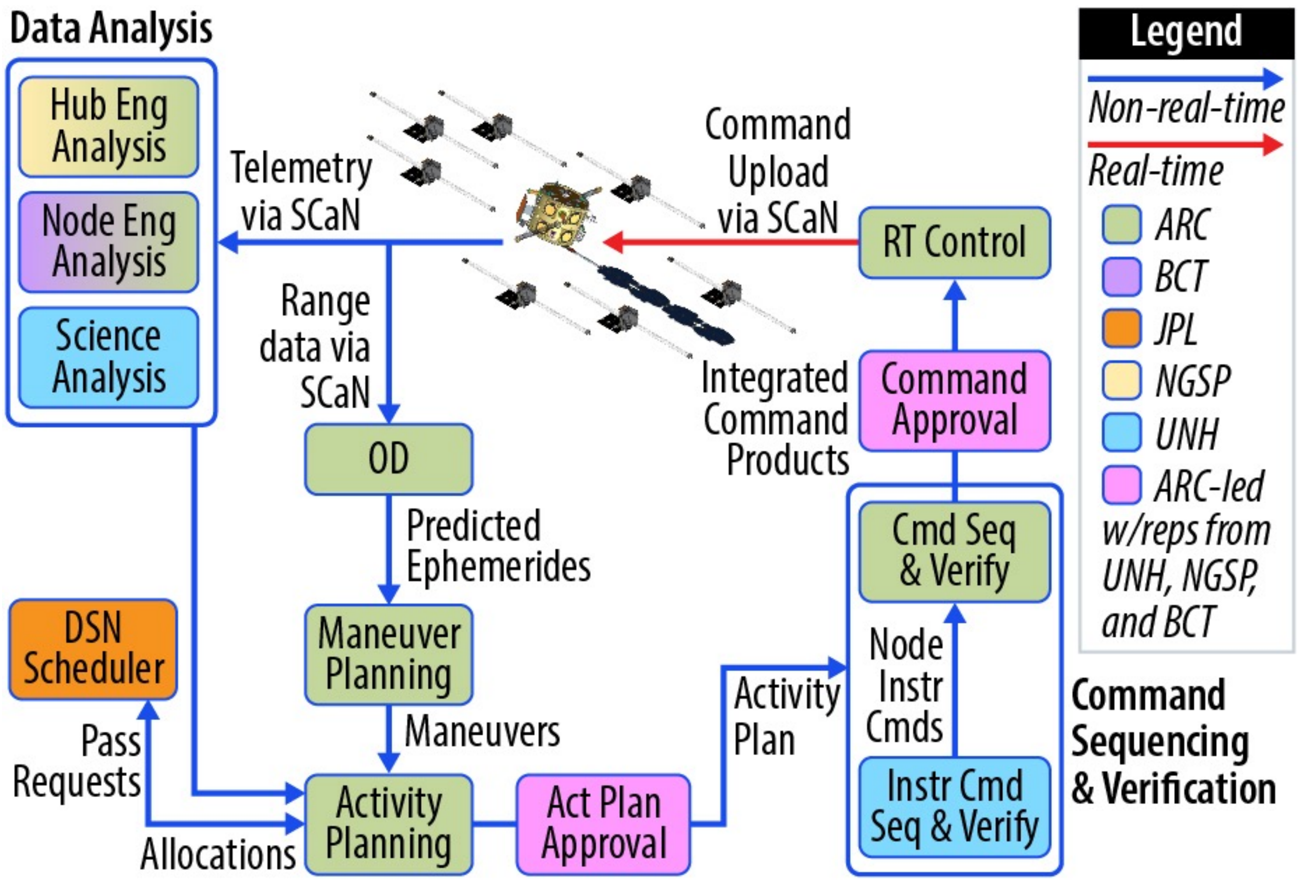
- **H** High-rate Hub-to-ground (includes downlink of all node data) once per orbit (14 days approx.)
- **L** Low-rate SOH and tracking every 3 days, extra around perigee
- Master sequence duration of 2 weeks, produced every week

Mission Operations and Ground Data System Approach

Mission Operations / Ground Data System Approach

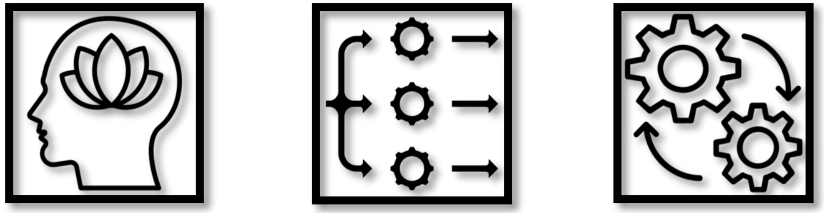
- Emphasize simplicity across the mission:
    - Recognition that even small complexities can multiply quickly
    - Key MOS/GDS positions staffed throughout mission life-cycle
- Utilize heritage tools and processes:
    - Swarm of nine spacecraft does not necessitate a new wholesale approach
    - Preference given to tools with demonstrated multi-spacecraft capability
- Scale processes and tools as necessary to meet operational efficiency requirements:
    - Simplify, Parallelize, and Automate
    - Design to specific target team size (proxy for cost)
- Closely monitor advances in commercial computing (cloud, virtualization, etc.)
- Mixture of predictive (e.g. waterfall) and adaptive (e.g. Agile) development methodologies base on level of process/software maturity w.r.t. multi-spacecraft operations

Mission Operations Process Cycle



HelioSwarm will use a traditional MOS process cycle scaled to meet the mission's swarm aspects

Scaling Approaches:



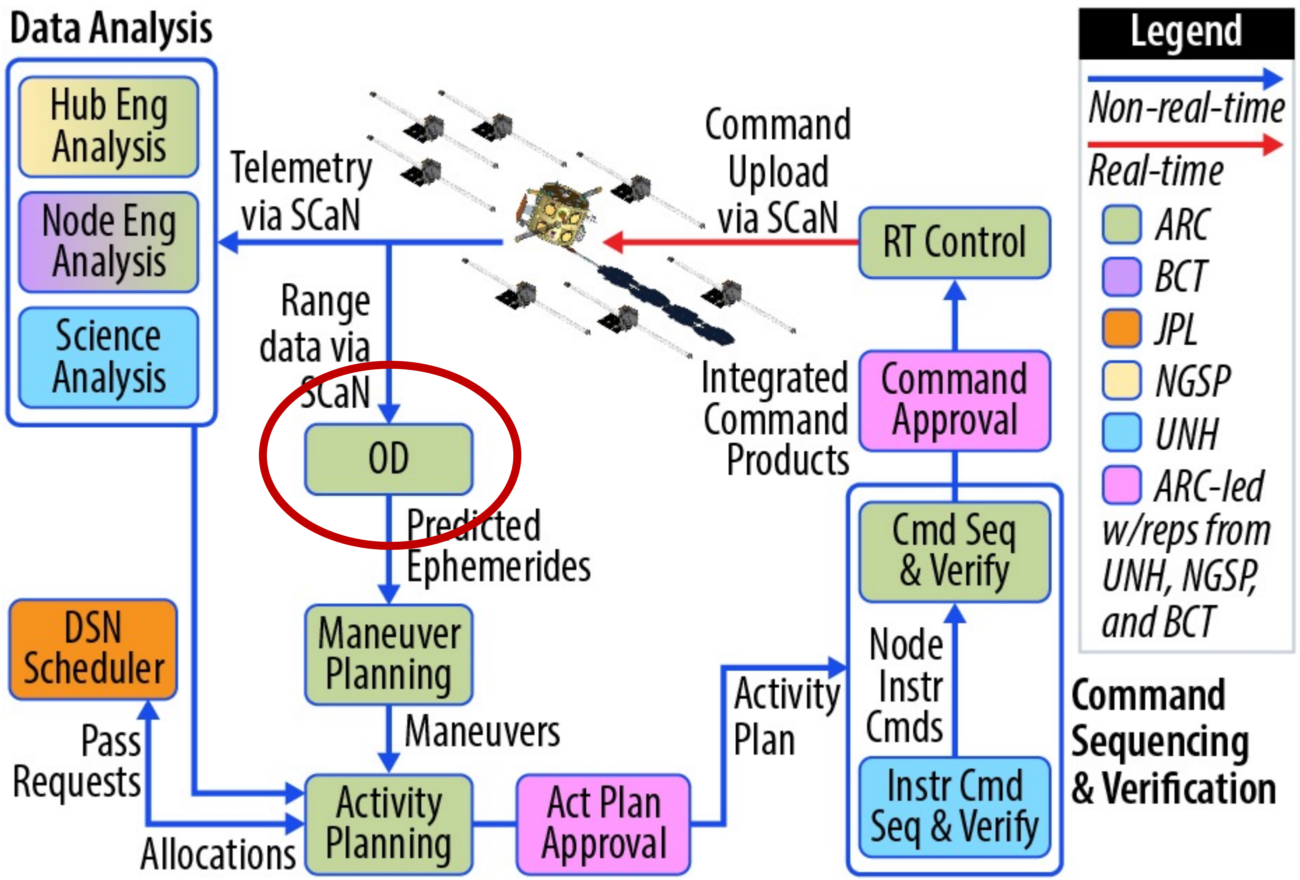
Simplify Parallelize Automate

Key Simplifications

- **Operate as a Swarm:** All spacecraft supporting the same objective. 9 spacecraft, but only 2 spacecraft types -- the nodes all carry the same flight software and hardware. Single tool-chain for all nodes. Same procedures for all nodes, just run multiple times (either in parallel or serially).
- **Simple Instrument Operations:** simple streaming modes, no complex pointing or tasking, no rapid observation-to-tasking turn-around needed, no “targets of opportunity”
- **No Hub maneuvers in Science Phase:** the complex portion of the Hub’s operations are all completed by the time mission moves into the Science Phase.
- **Simple S/C attitude operations:** Science instruments do not require attitude slews or tasking. The simple sun-pointing is wholly handled by the respective FSWs.
- **Minimal number of real-time contacts:** 5 contacts per orbit, and only with the Hub.
- **Minimal CARA coordination** needed during the Science Phase.

Lower complexity spacecraft and instruments lowers the required MOS process complexity

Orbit Determination Scaling

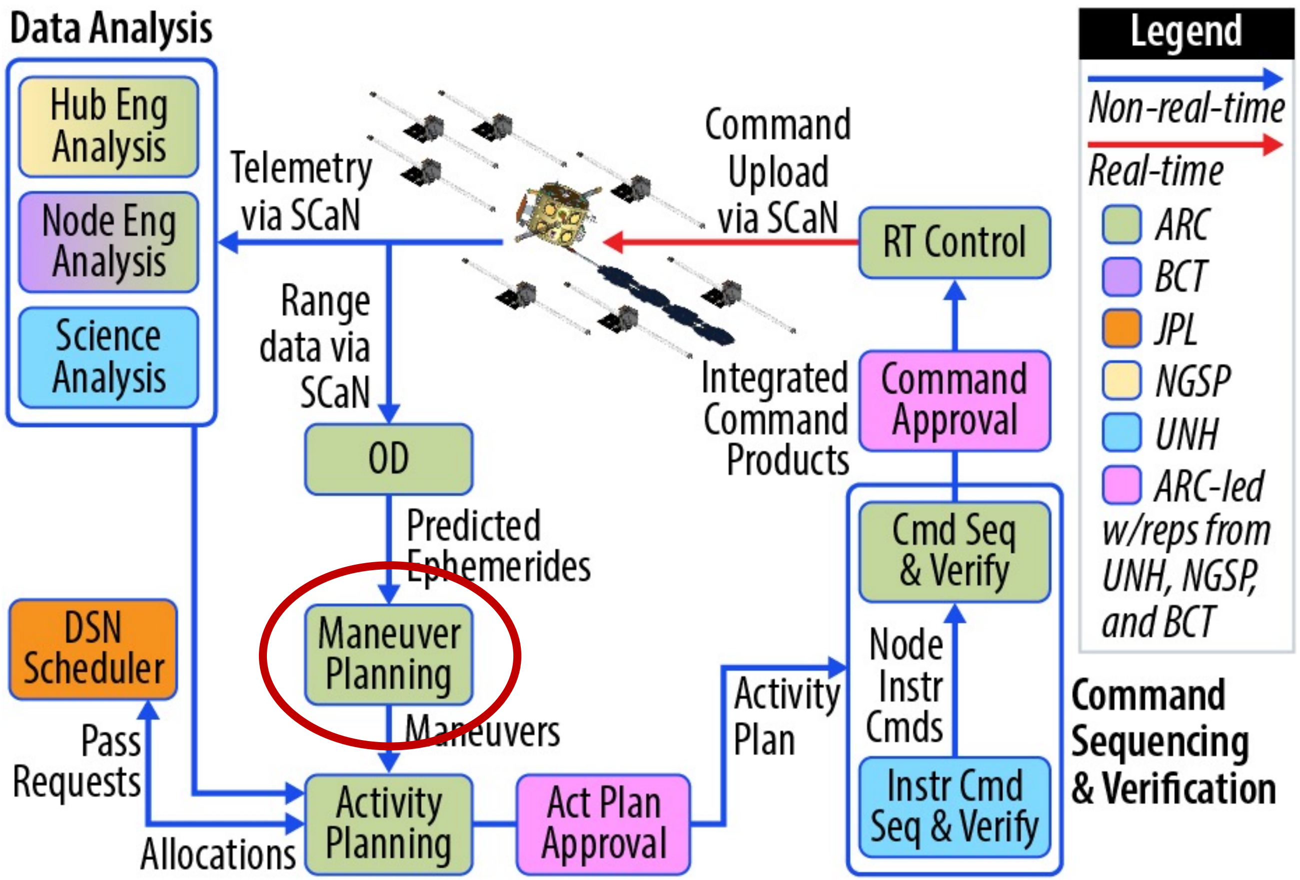


Orbit Determination

Process Hub tracking data and Node relative ranging data in single OD filter.

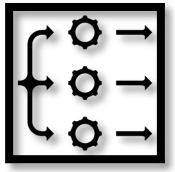
Use heritage FDS platform with scheduled and triggered job features

Maneuver Planning Scaling

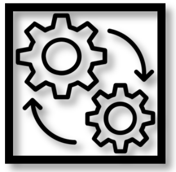


Maneuver Planning:

No Hub maneuvers during science phase / no Node maneuvers prior to science phase

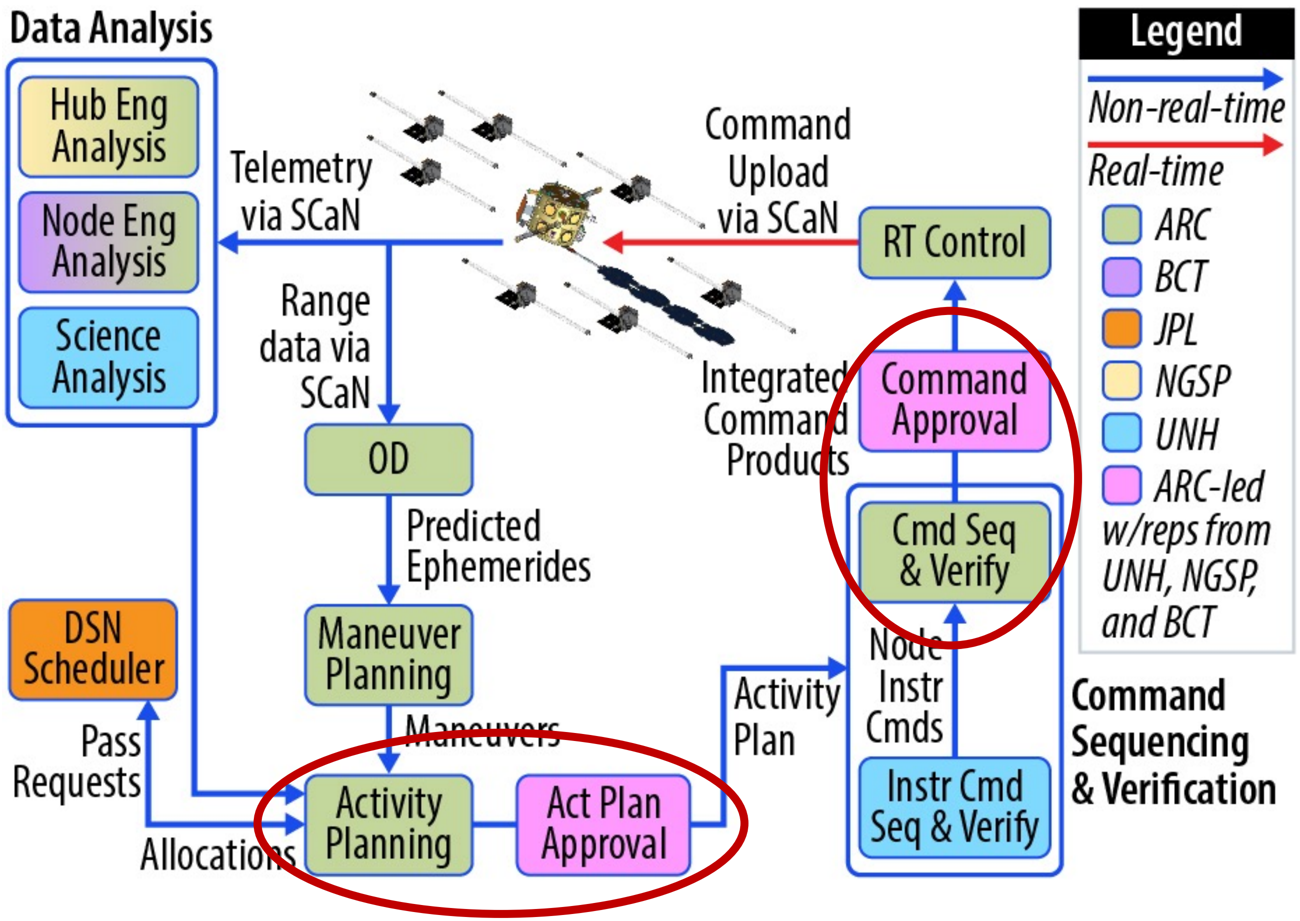


OTMs planned within single procedure run



Use heritage FDS platform with maneuver templating features

Command Sequencing Scaling



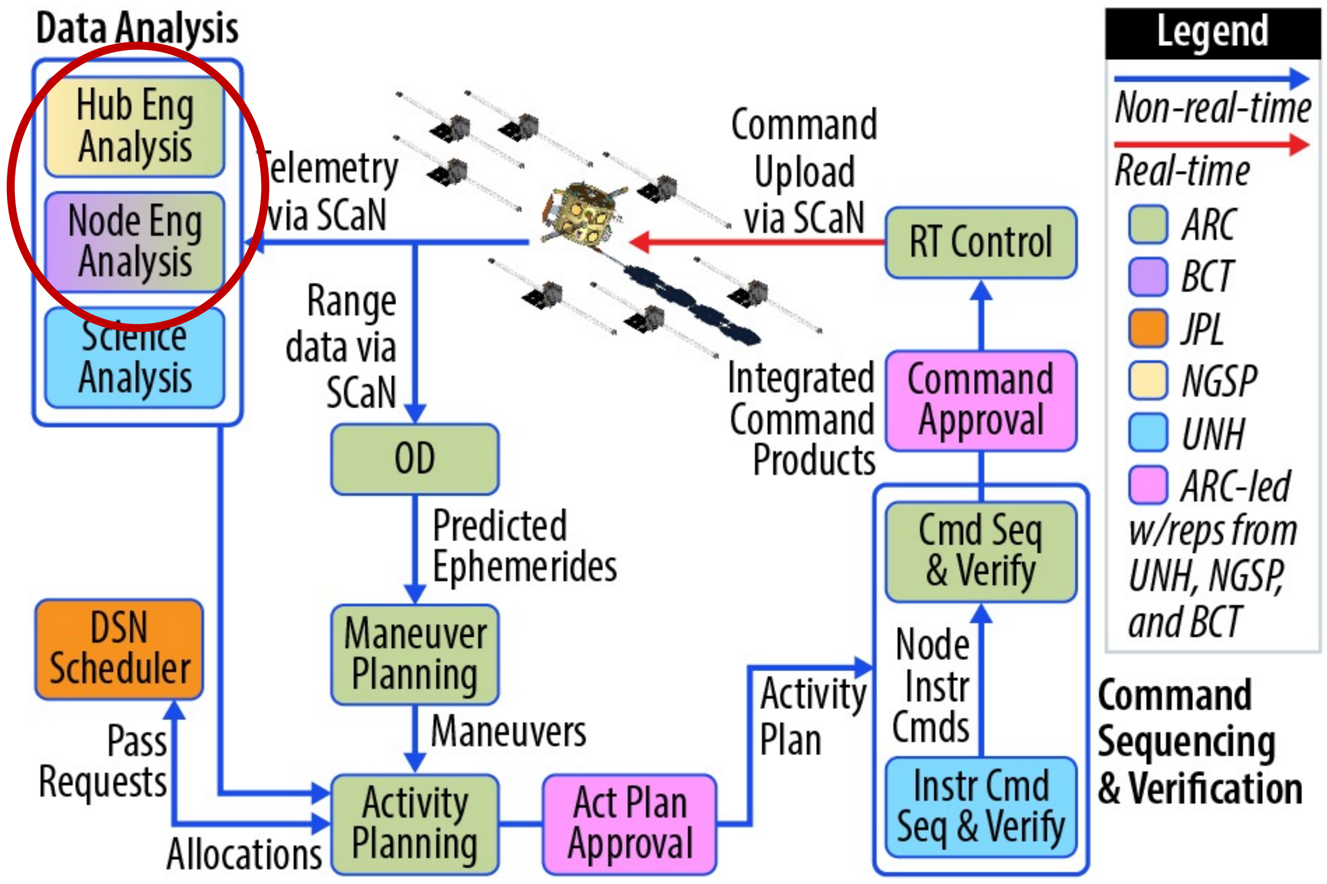
Activity Planning, Sequencing and Verification

Highly repetitive activities from plan to plan, simple Node attitude profiles

Activities for all Nodes and Hub in a single planning session

Scripting to ingest input products to create initial plan, and to apply command sequence templates. Workflow system to facilitate approval processes

Engineering Data Analysis Scaling



Engineering Data Analysis:

Plotting & Trending system integrates data from all swarm members and performs swarm-level trending

Application of Command & Telemetry automation platform and Plotting & Trending automation platform allows for ”lights out” passes

Potential for virtualization and parallel processing if needed (not currently anticipated)

Summary

- HelioSwarm is a novel and exciting mission with potential for foundational science.
- Mission-wide goal of minimizing complexity and maintaining an operations perspective throughout the mission life-cycle.
- Significant but not insurmountable ops / ground system challenges can be met through combination of simplification, parallelization and automation.
- We look forward to updating the community at future SpaceOps events.

Questions & Discussion

Attributions

- Slide 18:
  - USA Map by One World – Nations Online Project: https://www.nationsonline.com
- Slides 26-31:
  - Automate Icon made by Prosymbols Premium from www.flaticon.com
  - Parallel Icon made by juicy_fish from www.flaticon.com
  - Simplify Icon made by NeXore88 from www.flaticon.com

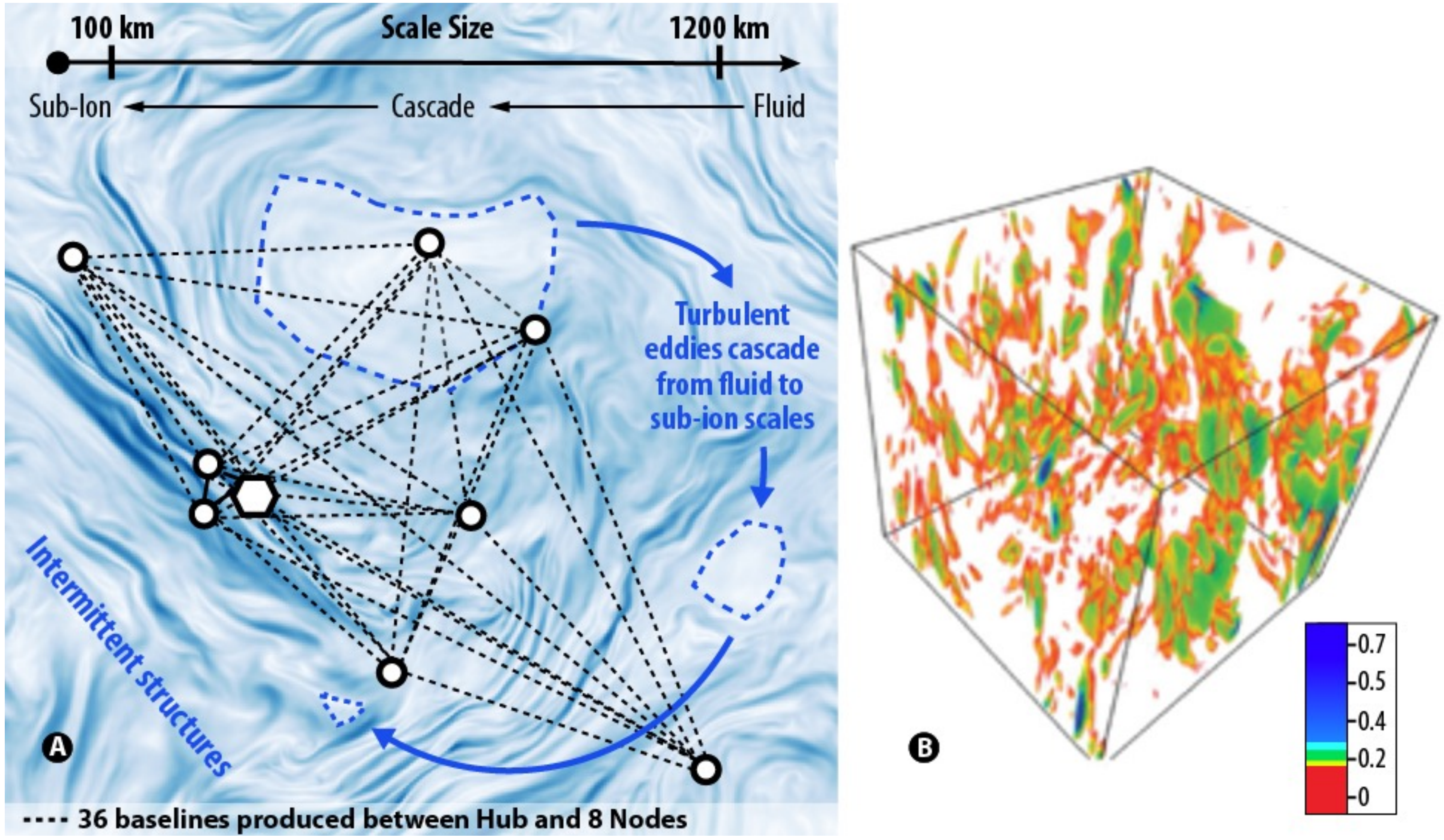
Back-up Material

Overcoming Previous Limitations

- Single S/C observations (Wind, ACE, IMAP, etc.) are fundamentally limited w.r.t. turbulence characterization

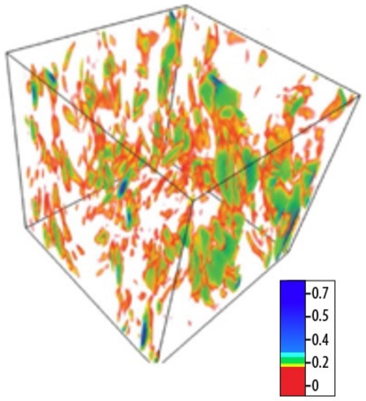
- Multi-S/C missions (Cluster, MMS, THEMIS) provide single-scale observations

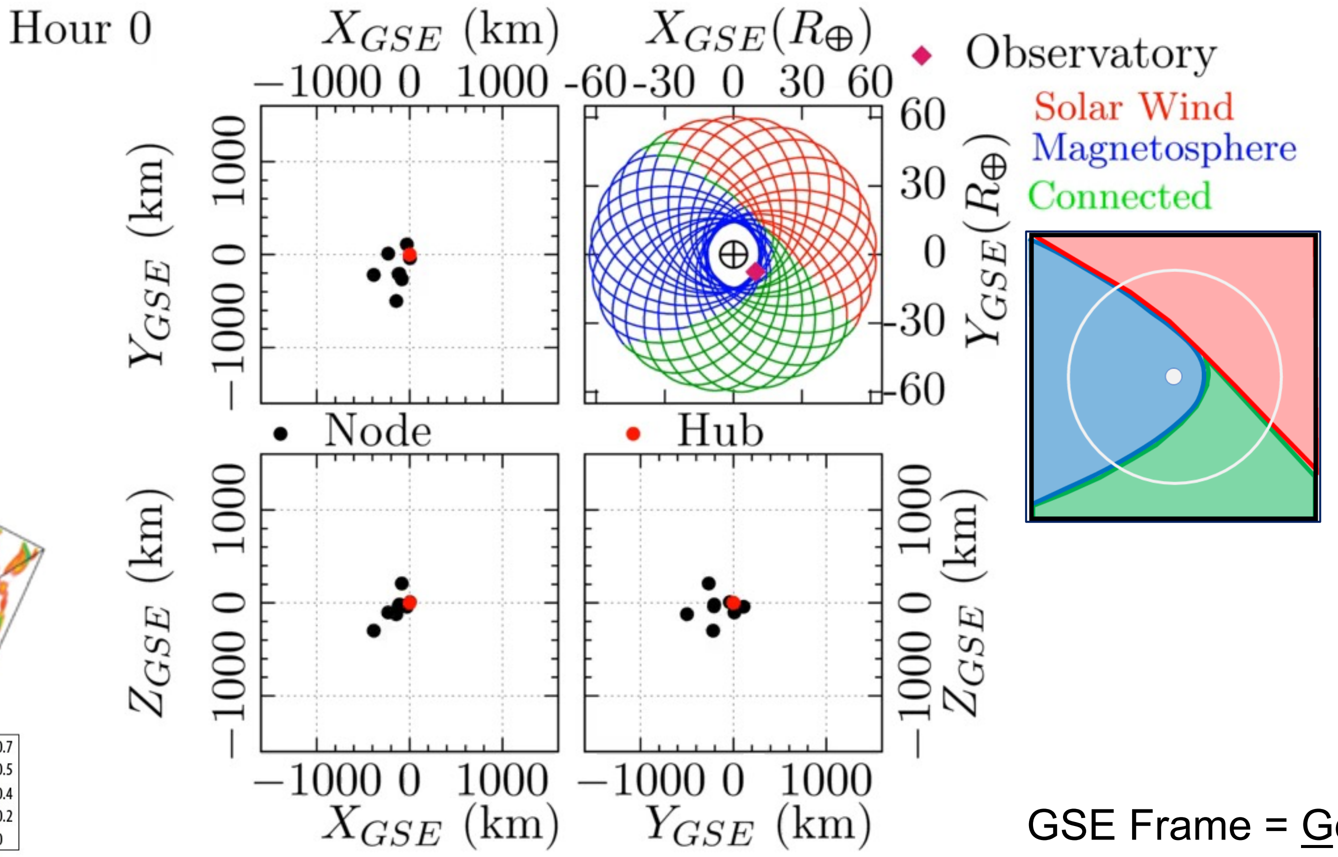
- Science questions require multi-point and <u>simultaneous</u> multi-scale measurements
    - MHD (>1200 km)
    - Transition (> 100 km, < 1200 km)
    - Sub-ion (< 100 km)



Combined Motion

Relative orbital motion of the swarm elements combined with bulk motion in the science orbit enables measurement scheme.





GSE Frame = Geocentric Sun Ecliptic