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Mission Design & Operations Approach for the HelioSwarm Mission

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Abstract

HelioSwarm: The Nature of Turbulence in Space Plasmas is a transformational mission to explore the dynamic three-dimensional mechanisms controlling the physics of plasma turbulence, a ubiquitous process occurring in the heliosphere and plasmas throughout the universe. Turbulence is the process by which energy contained in fluctuating magnetic fields and plasma motion cascades from large to smaller spatial scales. HelioSwarm achieves its science goals by making simultaneous measurements across a wide range of measurement baselines, spanning magnetohydrodynamic scales (1000's of km) to sub-ion heating scales (10's of km), using a novel nine-spacecraft swarm. The swarm operates in a high-altitude lunar resonant Earth orbit (two-week period, ~63 R_E apogee, ~13 R_E perigee), giving it access to both the pristine solar wind and regions of strongly driven turbulence (specifically the magnetosphere and foreshock), and utilizes customized relative orbital motion of the swarm members to produce the range of measurement baselines and configurations. The swarm comprises eight "node" spacecraft, manufactured by Blue Canyon Technologies, and a "hub" spacecraft produced by Northrop Grumman Corp. The hub serves as a communications relay, with all communications between the ground and the nodes flowing through it. Mission operations are conducted within the Multi-Mission Operations Center at the NASA Ames Research Center and science operations at the University of New Hampshire, Durham. HelioSwarm was selected in 2022 as one of NASA's newest Heliophysics Explorer missions to proceed from mission concept into mission implementation, with a target launch in 2029.

This paper provides an overview of the mission's science goals and objectives, the mission design, and the concept of operations, with an emphasis on how the swarm aspects of the mission both enable the science measurements and present unique operational challenges. The paper then describes the proposed development approach for the mission operations system and ground data system which relies on a selective combination of scaling strategies to meet the challenges.

Keywords: HelioSwarm, spacecraft swarm, swarm operations, multi-spacecraft operations, heliophysics

Nomenclature

R_E – Earth Radius
ΔV – Maneuver in which the velocity of the spacecraft is changed

Acronyms/Abbreviations

ACE – Advanced Composition Explorer
ARC – Ames Research Center
BCT – Blue Canyon Technologies
DSN – Deep Space Network
COTS/GOTS – commercial off the shelf / government off the shelf
ESA – European Space Agency
GDS – ground data system
GSE – geocentric sun ecliptic (coordinate system)
HGA – high gain antenna
IMAP – Interstellar Mapping and Acceleration Probe
JPL – Jet Propulsion Laboratory
LADEE – Lunar Atmospheric Dust Environment Explorer
LGA – low gain antenna
LV – launch vehicle

MMS – Magnetospheric Multiscale mission
NASA – National Aeronautics and Space Administration
NG – Northrop Grumman Corp.
MOS – mission operations system
OD – orbit determination
OTM – orbit trim maneuver
PN – pseudo-noise
SIM – swarm insertion maneuver

1. Introduction

HelioSwarm: The Nature of Turbulence in Space Plasmas is robotic spacecraft mission selected by Heliophysics division of NASA's Explorers program in 2022 to explore the dynamic three-dimensional mechanisms controlling the physics of plasma turbulence. "Swarm" in the mission's name refers to the novel use of a swarm of nine free-flying spacecraft co-orbiting to form a distributed observatory capable of simultaneous and multi-scale measurements of the plasma environment in near-Earth solar-driven regions [1,2]. One of keys to HelioSwarm's approach is to operate like single spacecraft missions with a moderately sized operations team (10 FTE approximately), rather than staffing a team of that size for each of the nine spacecraft. Operating within this profile necessitates that the mission concept and ground data system design carefully exploit opportunities for simplification and scaling.

As of the writing of this paper, HelioSwarm is between the concept development phase and the preliminary design phase in NASA's standard project life cycle (Phase A and Phase B respectively). The launch target is in early 2029 and the baseline mission duration is 18 months with a 12-month science phase. Given the mission's early phase of development, this paper aims to explain the current concept of operations and planned approach for developing the mission operations system (MOS) and ground data system (GDS), with particular focus on scaling. Ideally, future papers will report on the effectiveness of these strategies and the mission overall.

Section 2 describes the science investigation for a general audience as context for the mission concept. It then describes the mission concept including high-level details of the instrument suite, the spacecraft design, and the communications architecture. Lastly it summarizes the pertinent work done on the flight dynamics aspects of the mission including the science orbit and the relative motion between the swarm elements that enable the science measurements [3,4]. Section 3 then presents a summary of the concept of operations and the mission architecture focusing on those areas relevant to challenges presented by the swarm-nature of the mission. Lastly, Section 4 discusses the mission operations system design and how the mission intends to scale the operational processes and develop the ground data system tools so that they operate at an efficiency level sufficient to meet the operational requirements with a moderately sized team.

This paper focuses mainly on the novel swarm and multi-spacecraft aspects of the mission as they are the most significant drivers of the MOS processes and GDS software. Because the swarm does not start to take shape until the commissioning phase of the mission, the paper largely speaks to the science phase of the mission and doesn't provide significant detail on the phases that precede it, including the commissioning and launch and early orbit phases.

2. HelioSwarm Mission Concept

2.1 Science Investigation Background

Plasma accounts for most of the visible matter in the universe (stars, stellar winds, solar corona, the interstellar medium, accretion disks, etc.). Three universal plasma-driven physics processes govern all plasma systems: magnetic reconnection, shocks, and turbulence. Of the three, turbulence is the least understood despite it playing a key role in regulating thermodynamics throughout the universe. Turbulence is the process by which energy, originally contained in fluctuating magnetic field and plasma motion, cascades from large spatial scales to smaller ones. When the cascade approaches the scale of the motions of the charged particles comprising the plasma (i.e., weakly collisional), the energy ultimately goes into particle heating. Without turbulent cascades in space plasmas, the universe would be far colder than observed [1]. Because of the fundamental thermodynamic role it plays in fluids, including space plasmas, many contend that turbulent fluids are the most important unsolved problem in classical physics [2].

Over the last 25 years, NASA and ESA missions have been critical in advancing our knowledge of turbulence, however they have been limited by their scale. Missions like ACE and Wind have captured in-situ measurements within the turbulent cascade, but single spacecraft are limited to making measurements at single location at a particular time. More recent missions, in particular MMS and Cluster, have provided revolutionary data by making measurements over finite volumes of space by using coordinated multiple spacecraft. Even still, these have been limited to four spacecraft, and thus have only been able to probe a single scale size at a particular time. For complete understanding of the nature of turbulence, a series of simultaneous measurements must be captured across more than one 3D volume (both along and across the fields and flows), and with multiple length scales (ranging from fluid to sub-ion) [3]. The goals of the HelioSwarm mission are to provide these critical measurements.

2.2 Science investigation Goals and Objectives

HelioSwarm's science investigation, which is closely aligned with the 2013 National Academy of Sciences (NAS) 2013 Heliophysics Decadal Survey and NASA's Science Mission Directorate (SMD) priorities, thus has two well defined goals: (1) Reveal the 3D spatial structure and dynamics of turbulence in a weakly collisional plasma and (2) Ascertain the mutual impact of turbulence near boundaries and large-scale structures [4,5]. Of all the weakly collisional plasma regions in the Universe, the solar wind and its interaction with the Earth's magnetic field provide the ideal "laboratory" for studying turbulence. As such, HelioSwarm intends to meet its science goals by deploying a distributed observatory comprising a nine-spacecraft swarm in a high-altitude lunar-resonant Earth orbit. The nine-spacecraft swarm allows for the simultaneous multi-point measurements over multiple scales, and the selected science orbit provides routine and repeated access to the pristine solar wind and the strongly driven turbulent regions in the near-Earth environment; specifically, the foreshock, the magnetosheath and the magnetosphere. Figure 1 illustrates conceptually how the HelioSwarm 14-day orbit (described in Section 2.6.1) slowly rotates through the key plasma regions, allowing for accumulation of multi-scale data in each over the course of the year-long science phase.

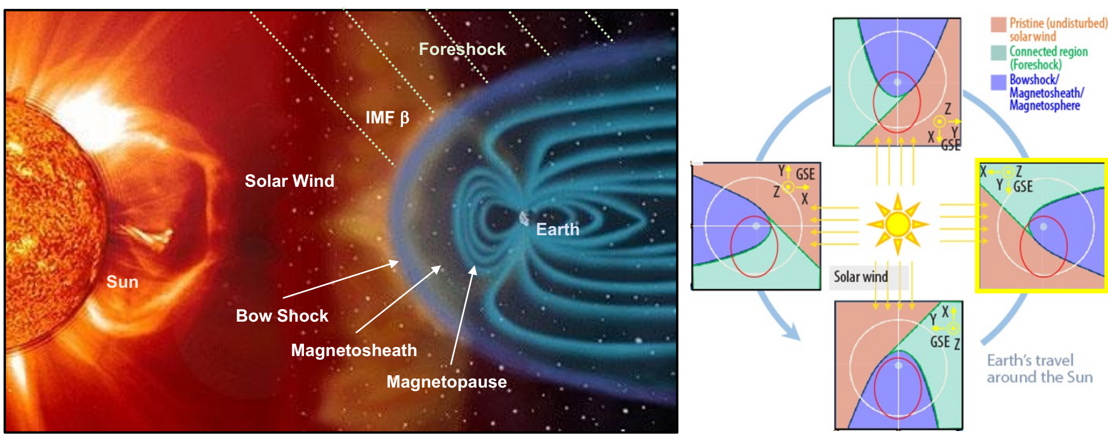

Fig. 1. Left: Illustration of interaction of the solar wind with Earth's magnetosphere, highlighting HelioSwarm's regions of interest. Courtesy of NASA/ESA. Right: HelioSwarm's inertially fixed orbit (red line) effectively rotates through the regions of interest as the Earth orbits the Sun. The Moon's orbit around the Earth (white line) is shown for context.

2.3 Spacecraft

HelioSwarm's nine-spacecraft swarm is composed of eight free-flying "node" spacecraft provided by Blue Canyon Technologies (BCT) (Boulder, CO, USA) and a single "hub" spacecraft provided by Northrop Grumman Corp. (NG) (Sterling, VA, USA). Inclusive of the instrument suite (see Section 2.4), the nodes are ~67 kg small spacecraft based on BCT's Venus Bus line. The hub, with a dry mass of ~655 km, is an adaptation of NG's evolved expendable launch vehicle (EELV) secondary payload adapter (ESPA) ESPAStar product line and will carry the nodes from the launch vehicle's burn-out orbit to the science orbit.

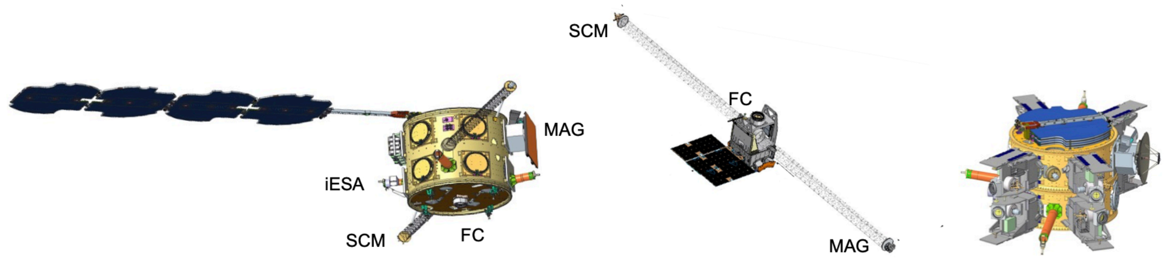

Fig. 2. HelioSwarm spacecraft with instrument placements notated. Left: the hub spacecraft. Center: a single node spacecraft (observatory contains eight). Right: launch configuration of hub with nodes attached. NOTE: Lengths between diagrams not strictly to scale.

All spacecraft carry a 3-axis stabilized attitude control system, a suite of power and data handling avionics, a passively cooled / actively heated thermal control system, flight software, a deployable solar array, a propulsion system for orbit control, and S-band communication equipment. The hub carries a traditional hydrazine blowdown propulsion system used to maneuver itself and the attached nodes into the desired science orbit, while the nodes carry a low thrust electric propulsion system used to achieve and maintain the relative orbital motion between spacecraft necessary for the science measurements. As described more fully in Section 3.3, the hub carries a single S-band communication system for communications with the ground and redundant S-band crosslink systems for communications with the nodes. The nodes carry the same crosslink system, but not a ground communication system. Both the hub and the nodes carry modern flight software systems with the following capabilities: collection, storage and play-back of telemetry, response to real-time and stored commanding, and configurable fault detection and response, among other features.

Each of the two spacecraft types have a well-defined role in the mission concept. For the large maneuvers needed to transfer from low Earth orbit to the science orbit, the hub carries the nodes in an aggregated flight segment (Figure 2). Similarly, for data return over long distances, the hub acts as a communications relay. In contrast, the node spacecraft, which carry more limited capabilities, act as free flying instrument suites. They perform small maneuvers to establish and maintain individual variations of the shared orbit and carry RF communication equipment suitable for swarm scale distances.

2.4 Instruments

The HelioSwarm instrument suite consists of the instruments and associated supporting mechanical and electrical components capable of capturing the science measurements required to meet the goals of the science investigation. The hub and each of the nodes will carry a Fluxgate Magnetometer (referred to as MAG), which measures the vector DC component of the local magnetic field, a Search Coil Magnetometer (SCM), which measures the vector AC component of the local magnetic field, and a Faraday Cup (FC) which measures solar wind plasma density and velocity. In addition, the hub will carry an Ion Electrostatic Analyzer (iESA), which measures 3D ion velocity distributions. The MAG and the SCM instruments mount on the tips of opposing booms, offsetting them from other spacecraft components for the purposes of magnetic cleanliness. The booms deploy as part of each spacecraft's commissioning activities. The FC and the iESA (hub only) mount on the central part of each spacecraft and require that the spacecraft maintain a solar-pointed attitude for them to perform their measurements. The MAG and the SCM have attitude knowledge requirements but do not have any specific pointing requirements. From a power, thermal, and data volume perspective all instruments can operate simultaneously and nearly continuously, which makes for a simple overall instrument suite operational concept. All the instruments have previous flight heritage with a well understood operational profile.

2.5 Swarm Communications

HelioSwarm employs a "hub and spoke" network topology in which all communications between the ground and the nodes relay through the hub, with no node-to-ground/ground-to-node nor node-to-node communications. The trade study that led to the selection of this architecture is outside the scope of this paper, however simplicity was the key driving factor. For frequency licensing and coordination purposes, HelioSwarm will only request a single frequency pair for the crosslink. Hence the crosslink will largely be shared in a time-division multiplexing-like scheme (TDM), with time scheduled for the hub to communicate with node 1 for a certain period (on the order of minutes to 10's of minutes), then with node 2 for a non-overlapping period, then node 3, etc., although there is no constraint that forces the communication to proceed in any strict order. The switching between nodes is driven by a stored command sequence developed on the ground, then uploaded for execution on board the hub on a regular basis (see Section 3.1). Hence, the system is not a true TDM system in which both sides need to be synchronized with hard-time requirements. This scheme is used to transfer commands and file data from the hub to the nodes, to transfer telemetry and file data from the nodes to the hub, and to perform relative ranging between the hub and each node based on the CCSDS 414.1-B PN ranging standard critical to orbit determination. Pending the actual frequency coordination activities with regulating bodies, HelioSwarm intends to use S-band frequencies for both the ground-to-hub links as well as the hub-to-node links.

2.6 Orbit Dynamics

HelioSwarm's ability to make simultaneous measurements of the turbulent cascade across more than one 3D volume and with multiple length scales in the prescribed turbulent regions relies on two orbital design efforts. The first is the design of the bulk orbital motion of the swarm around the Earth in the Earth-Sun system, referred to as the science orbit design. The second is the design of the relative orbital motion of the nine spacecraft with respect to each other within the science orbit, referred to as relative orbit design. The former places the observatory in the science regions of interest, while the latter creates the spatial configurations required to make the measurements. The spatial configurations defined by the investigation are (1) "3D configurations", which consist of pairs of spacecraft at varying inter-spacecraft distances and orientations with respect to the solar wind, and (2) "polyhedral configurations", which consist of eight spacecraft forming two tetrahedra (four spacecraft each) that meet specific geometric constraints relevant to the measurement strategy [5].

2.6.1 Science Orbit

The HelioSwarm science orbit is a high-altitude P/2 lunar-resonant Earth orbit (see Figure 3), giving the observatory access to both the pristine solar wind and regions of strongly driven turbulence, specifically the magnetosphere and foreshock regions. Lunar resonant refers to the orbit period being an integer fraction of the Moon's orbital period around the Earth; in HelioSwarm's case one-half of the Lunar orbit, i.e., two HelioSwarm orbits per one lunar orbit. The orbit's period is approximately 2-weeks, with a perigee of ~13 R_E, and an apogee of ~63 R_E, bringing its altitude very close to that of the Moon's orbit [8]. The orientation of the orbit relative to the Sun-Earth geometry and the science regions of interest slowly rotates over the 12-month science phase of the mission, resulting in extended measurement time in each (see Figure 1).

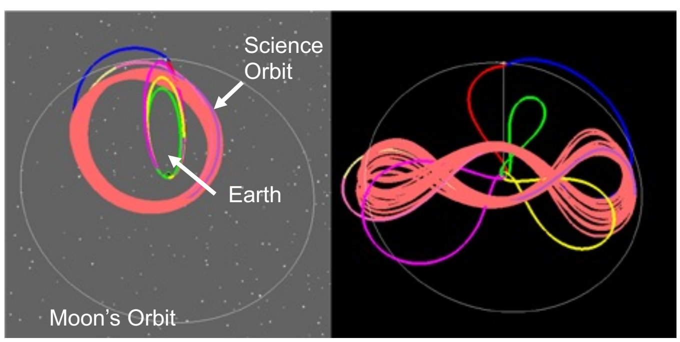

Figure 3. The entire HelioSwarm trajectory from launch to end of mission shown in Earth-centered Inertial (ECI) (left) and Earth-Moon rotating (right) frames. The science orbit is the salmon-colored portion, and the Moon's orbit around the Earth is shown in light grey.

Aside from this orbit meeting the science requirements, it has several operational advantages. The most critical advantage is that once established, the orbit does not require maintenance maneuvers and evolves under the influence of natural perturbations. The hub's propulsion system is used to achieve the orbit but won't be needed to maintain the orbit. In addition, the perigee altitude is well above the geosynchronous altitude (~6.6 R_E), thereby greatly reducing the risk of conjunction with other objects, simplifying collision avoidance planning. The orbit also limits maximum eclipse durations to manageable levels. Finally, while the apogee altitude of the orbit is at lunar altitude, the swarm only passes apogee when the Moon is as far away as possible, maintaining a consistent lunar keep-away distance of more than 200,000 km throughout the mission lifetime and beyond. All the above factors combine to allow the focus of the science phase of the mission to be on managing the science data collection and maintaining the relative orbits, and not the science orbit.

2.6.2 Relative Orbital Motion

Constant motion of the eight nodes relative to the hub and to one another enables HelioSwarm's measurement strategy. The relative motion design forms the required geometries while exploiting the natural dynamics of the science orbit [6,7]. Figure 4 depicts each of the node's motion with respect to the hub spacecraft over the course of the 12-months of the science phase. As shown, the design has five outer nodes and three inner nodes, which allows for the simultaneous multi-scale measurements. The period of each of the node's relative orbits with respect to the hub is the same as the period of the science orbit; ~14 days. That is, the time it takes for one of the nodes to travel around one cycle of the orbit trace in Figure 4 is the same time that it takes the swarm to travel around the science orbit once in Figure 3. As this repetitive motion proceeds, 3D baselines and tetrahedra configurations are formed and unformed at various parts of the science orbit. Inter-spacecraft distances naturally expand near the apogee of the science orbit to maximum hub-to-node distances of approximately 1600 km to support science requirements, and contract near the perigee with distances between 20 and 100 km to support high crosslink data rates. In general, science data collection is the focus away from perigee when the swarm is moving slower with respect to the Earth, and data downlinks (both node-to-hub and hub-to-ground) are conducted near perigee when communications links support higher data rates (more details in Section 3.1).

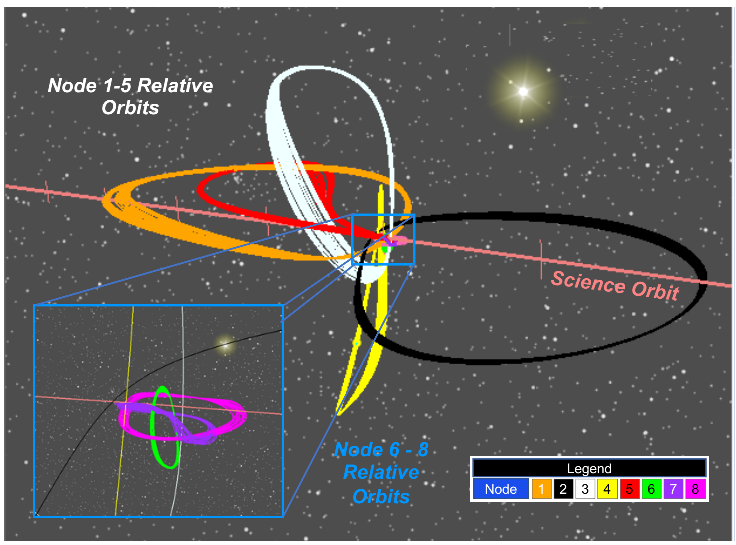

Fig.4. Relative orbital motion of the nodes about the hub follows the eight colored traces. The main figure shows the entire swarm (both inner and outer), while the inset figure on the bottom left shows an expanded view of the inner nodes. The path of the swarm along the science orbit is shown as well.

Unlike the bulk motion of the science orbit, the intricate relative orbital motion does require routine maintenance and demands operational attention. Swarm Insertion Maneuvers (SIMs) establish the relative motion following node separations from the hub, and Orbit Trim Maneuvers (OTMs) maintain it [8]. The relative orbit design calls for each node to perform two OTMs per orbit. The spacing of the OTMs around the orbit is dependent on the specific goal of each maneuver and avoids other high priority activities such as science data collection and crosslink communications. Due to the sheer number of maneuvers, the weekly cadence of the OTM maneuver planning process represents the largest operational challenge for the mission. However, assuming the OTMs are successfully executed, the resulting relative orbits are highly repetitive, thereby simplifying activity planning, command sequencing, and the concept of operations overall.

3. Concept of Operations

The following provides an overview of the HelioSwarm concept of operations, with specific emphasis on the aspects that are likely to have the largest impact on the design of the mission operations and ground data systems.

3.1 Science Mission Profile & Operations Timeline

The combination of the bulk motion of the swarm in the science orbit and the relative motion of the nodes around the hub drives the science mission operational concept illustrated in Figure 5. The highest value science opportunities occur when the swarm is away from perigee and moving slower with respect to the plasma environment, allowing extended observation time in the regions of interest. As the swarm approaches apogee, the relative orbits naturally move the observatory into polyhedral configurations, then into the 3D configuration afterwards. Conversely the lowest value science opportunities occur when the swarm is close to perigee and moving quickly. While less desirable for science, this portion of the orbit is the best for inter-swarm communications, as well as hub-to-ground communication. Hence, science measurements are prioritized in the days away from perigee, and communications and maneuver activities are prioritized near perigee.

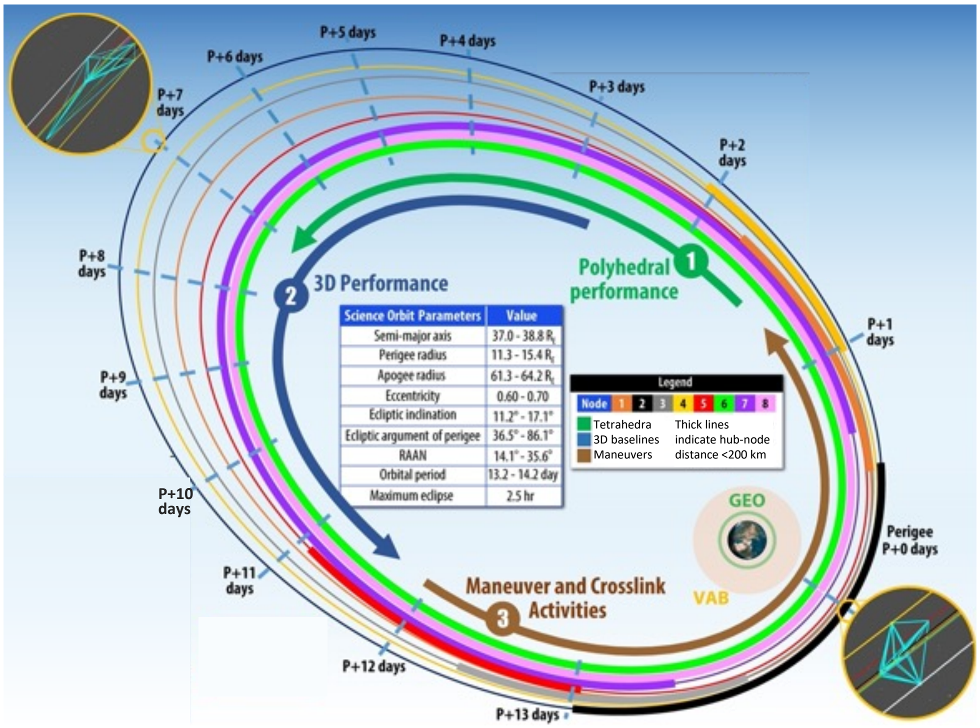

Fig. 5. Illustration showing bulk orbital motion of all nodes (and hub implied) over a single science phase orbit. Thick lines labelled "1", "2" and "3" indicate emphasized activities over that portion of the orbit. Circular insets at perigee (lower right) and apogee (upper left) illustrate contraction and expansion of the swarm, respectively.

Swarm communication and maneuver activities follow a general pattern on an orbit-by-orbit basis. In addition to creating the swarm configurations required by science, the relative orbit design allows for sufficient time for each node to transmit its science data to the hub for eventual downlink by phasing each node's closest approach. As shown in Figure 6, while the swarm naturally contracts at each science orbit perigee, the period that each individual node is closest to the hub is separated in time, such that close approaches occur over an approximate 4–5-day span. It is during these times that the operations team will plan transmissions of the node science data to the hub. Figure 6 shows the node-to-hub range for each of the nodes over the course of an example science orbit, along with the notional schedule of node-to-hub science data transmissions (see colored bars superimposed at the y=0 line of the plot). The schedule includes 12 hours of transmission time per node, which meets the science data volume requirements with a 40% margin calculated against current estimates. The schedule will also intersperse 30 minutes of relative ranging per day per node and ten minutes of node-to-hub state of health data transmission per day per node in between the science data transmissions. The operations team executes a 7-hr high data rate contact with the hub around perigee downlinking all the hub and node science data held in the hub's stored memory.

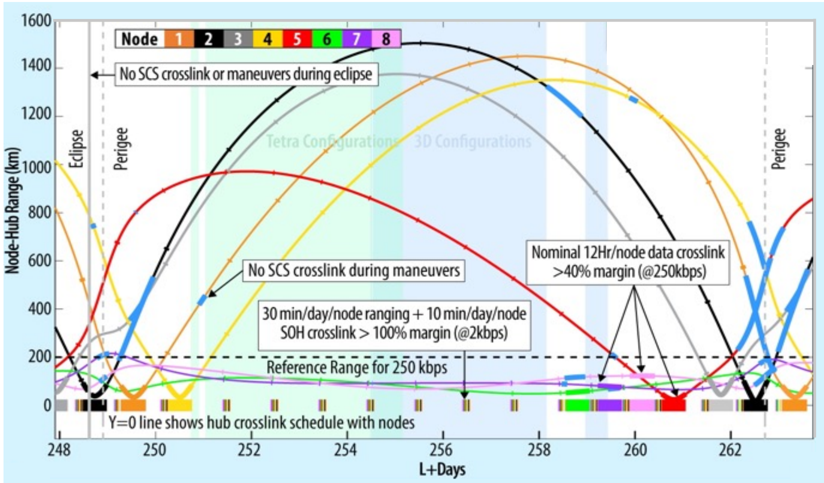

Fig. 6. Hub-to-node range, data downlink (node-to-hub) windows and maneuver windows over a typical science phase orbit for all 8 nodes. Maneuvers are represented by blue lines overlayed on node-hub range traces.

Node OTMs are scheduled to occur outside of communications activities due to node power constraints. Because most of the OTMs will require the nodes to point away from the nominal sun-pointing science attitude, maneuvers are also deconflicted with science data collection.

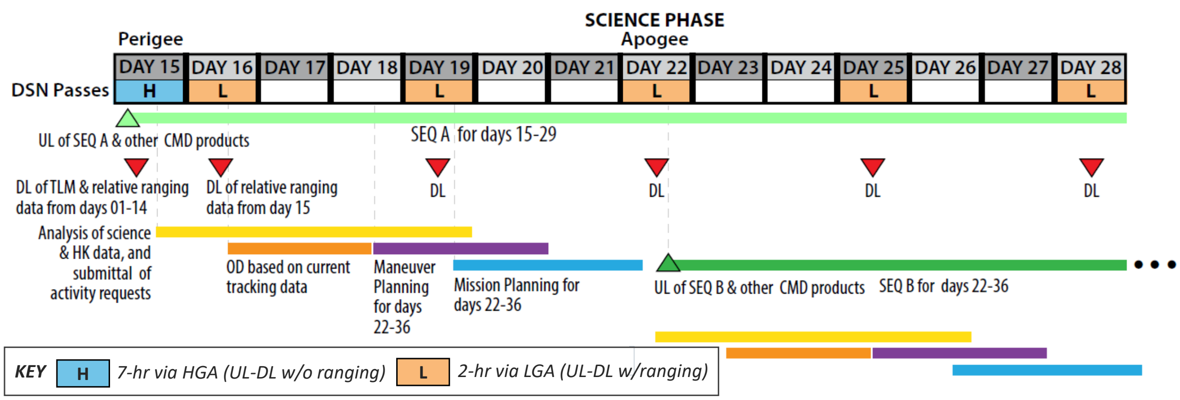

Fig. 7. Routine swarm-level operational activities over a typical science phase orbit.

An example of the ground-based activities performed during a single orbit are shown in Figure 7. The ground team executes the 7-hr high data rate with the hub to downlink all science data and housekeeping data collected by the entire observatory over the previous orbit. All data is transmitted and stored with metadata containing the spacecraft identifier such that it can be identified and separated once on the ground. During the 7-hr contact the ground also performs an uplink to the hub containing command sequences with commands for all spacecraft for the next 14 days (see light green line – "SEQ A for days 15-29"). Sequences for each spacecraft go to the hub as separate files. The hub subsequently transmits the node sequence files to each of the appropriate nodes based on the schedule established in the hub's main sequence. Following the downlink and automated processing thereof, the engineering team analyses the downlinked data, performs trending, and derives any necessary housekeeping activity requests over the next 2-3 days. The flight dynamics team uses the downlinked relative ranging data along with the hub tracking data from the DSN to perform orbit determination for all spacecraft (Section 4.2.1) and uses the results in the maneuver planning process for the next week. The activity planning team then integrates any science team requests, engineering team requests and the maneuver plans into a single activity plan and generates sequences for each spacecraft in preparation for a second upload at apogee (see dark green line "UL of SEQ-B …"). As shown, sequences hold 14-days' worth of commands, but are produced and uploaded every 7-days, thereby maintaining a 7-day "run out" of commands to execute.

3.2 Mission Architecture

Figure 8 depicts the HelioSwarm mission architecture that integrates all the concepts described above. HelioSwarm launches with the nodes powered off and attached to the hub. The launch vehicle (not selected as of the time of this writing) inserts the flight system into the first of three phasing loops, with the hub performing all subsequent ΔV maneuvers to target a lunar gravity assist and achieve the science orbit about three months after launch. Operations during this phase are similar to LADEE's launch and transit phases [9,10]. Commissioning occurs in the six orbits (approximately three months) following science orbit insertion. The nodes separate from the hub in pairs under the supervision of the operations team. Node separations are ideally completed within the first four orbits (i.e., one pair each orbit), however the timeline is flexible to allow for anomalies or operations ramp-up time. NASA's Deep Space Network (DSN) provides nearly all the communications services for the mission, with NASA's Space Relay (formerly known as TDRSS and Space Network) being used for acquisition and for early mission maneuver support.

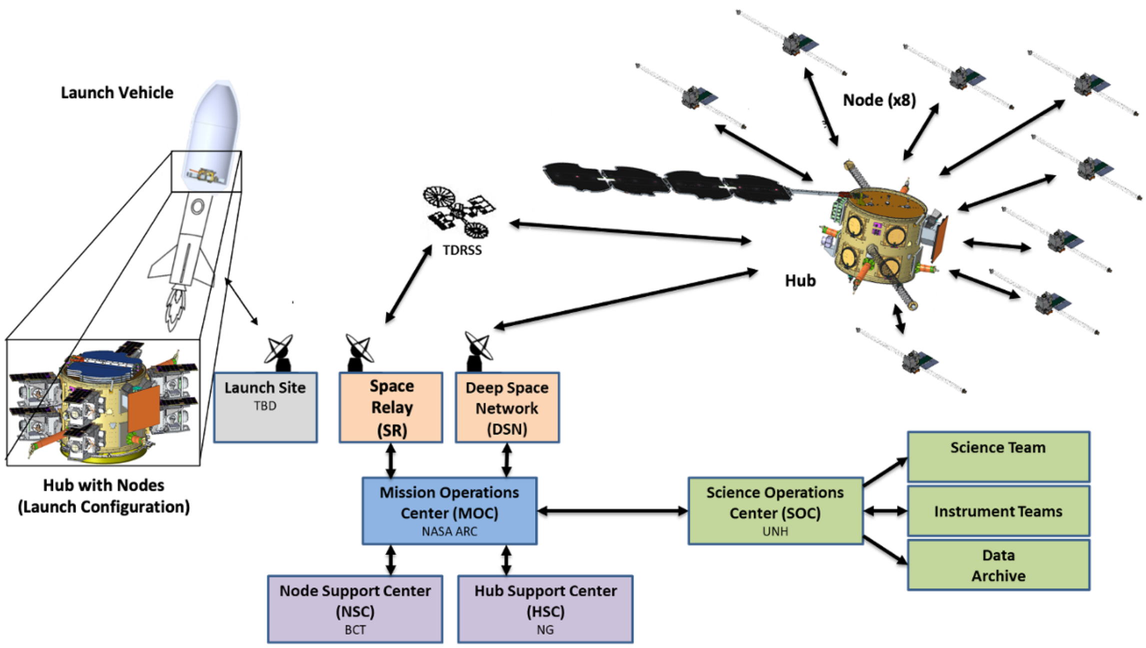

Fig. 8. HelioSwarm overall mission architecture showing the launch segment, ground segment, and space segment.

All communication with the nodes is relayed through the hub using a store-and-forward approach (Sec. 2.5). Spacecraft operations for both hub and nodes occurs in the Multi-Mission Operations Center at NASA ARC, with spacecraft engineering support teams operating remotely at BCT and NG. Science Operations resides within the Science Operations Center (SOC) at the University of New Hampshire, Durham. The SOC serves to collect activity requests and commanding inputs from the various science stakeholders, process and provide the Level-0 data delivered to the instrument teams, produce merged data products (Level-4), and archive all data sets (Level-0 through Level-4). Individual instrument teams are responsible for producing the resolved magnetic field, solar wind density, and velocity data products (Level-1 through Level-3) and delivering them back to the SOC to be merged.

4. Mission Operations and Ground Data Systems Approach

HelioSwarm's approach to the development of the mission's MOS/GDS has several key tenets. The first is an emphasis on simplicity in the operational concept for the spacecrafts and instruments. The team recognizes that with a multi-spacecraft mission, undue complexity in these areas could multiply quickly and drive operational costs. The second is to build the MOS/GDS from heritage processes and tools and then scale them via automation and parallelization when necessary. While managing nine spacecraft will be more challenging than managing a single spacecraft mission, the team believes that the scope does not call for a complete replacement of tools and processes known to work effectively. And lastly, the mission will be closely monitoring advances in commercial computing technology, such as cloud, virtualization, and those supporting remote work, looking for potential to increase operational efficiency and cost. The following sections expand on these ideas further.

4.1 Simplifying Factors for Mission Operations

The mission team understands that design decisions from across the project (science, instrument, spacecraft, etc.) that aren't made without considering their downstream impact on operational complexity have the potential to drive operational costs out of bounds very quickly. Flight system idiosyncrasies, constraints, and special procedures that are "kicked down the road" to the operations team are compounded up to nine times in the worst case. To minimize the potential for this scenario key MOS/GDS positions are staffed throughout the project life cycle, including the conceptual and preliminary design phases. Mission operations has had representation on the project's System Engineering and Integration Team (the primary technical decision-making body), starting even in the proposal phase, and will continue through all project phases. Having such staff helps to ensure that the operator's perspective is represented, and that operational complexity is always considered. The most important simplifying factors in the mission concept that have already been realized via this approach follow in the subsequent sub-sections. These factors serve to reduce the scope of work in the operations phase.

4.1.1 Operations as a Swarm

Perhaps the most important operational simplification is that the operations team will operate HelioSwarm as a swarm rather than as nine individual spacecraft. This approach is possible because all spacecraft in the swarm operate in support of the same science goals, rather than multiple or conflicting goals. Such an approach isn't possible in many multi-spacecraft missions, and even some single-spacecraft missions with non-complementary payloads; an Earth imaging constellation with a disparate customer base is an example of this. In addition, while individual activity timelines and command sequences will need to be routinely generated for each spacecraft, the planning processes and tools will generate command products for the entire swarm in a single planning session rather than multiple sessions. The process will also use the same procedures for all nine iterations rather than unique steps for each spacecraft. This type of combined operations is possible because all the node spacecraft carry the same hardware and software (resulting in only two types of spacecraft to control) and because all the spacecraft launch together. This similarity among swarm members contrasts with operations for constellation missions in which spacecraft are deployed over months or years and routinely include different lines or generations of hardware and software. HelioSwarm leverages the fact that all nodes are nearly identical to deploy a single ground software tool chain for the nodes, in addition to one for the hub. Procedures, telemetry screens, and other operational products will be used across node operations, simplifying the monitor and control aspect of operations as well.

4.1.2 Instrument Operations Simplicity

All the science instruments selected for the HelioSwarm instrument suite have a simple operations model, with each having only a small number of data collection modes and a simple streaming data interface. The instruments do not have any articulating components, nor do they require custom attitude pointing or slew maneuvers by the spacecraft; a single sun-pointing attitude is all that is required for all instruments in the observatory. Subsequently, the MOS/GDS does not have any derived requirements to design custom attitude profiles or sequences to operate the instruments. Lastly, satisfaction of the science goals doesn't call for any sort of rapid observation-to-tasking turn around process and there are no requirements for observing "targets of opportunity", which for other missions can tend to drive operational staffing profiles. The sum of these factors results in a very manageable number of activities for the operations team to plan and execute.

4.1.3 Maneuver Operations

While maneuver planning and operations will be one of the most complex of the MOS sub-processes throughout the mission, a key simplification built into the mission operations concept is that maneuver planning for the hub will never overlap with maneuver planning for the nodes. All hub maneuvering is for establishing the science orbit, so once that transfer is complete, all maneuver planning efforts turn towards deployment of the nodes and subsequent relative orbit maintenance maneuvers. Because the hub and nodes have different types of propulsion systems and FSW, allowing the operators to focus on one type at a time reduces operator workload, and potentially shift time.

4.1.4 Limited Real-time Interaction

Minimizing real-time interaction between the operations team and the swarm, while still providing sufficient coverage to monitor the health of the observatory, also serves to simplify operations. As shown in Figure 7, the team will only conduct six ground contacts per week, and all with the hub. One long ground contact (7 hours) near perigee will be used to download all the science data from the previous orbit, and five short contacts (2 hours) distributed around the orbit will be used to gather basic state of health telemetry, perform radiometric tracking with hub, and download the node tracking data stored on the hub. The two-hour contacts will be "lights out" and monitored via pass automation. The small quantity of contact and total tracking time places a minimal burden on the DSN and allows the operations team to focus on data analysis and planning rather than real-time interaction.

4.1.5 Minimal Collision Avoidance Risk

In general, a multi-spacecraft mission must address collision avoidance. HelioSwarm's collision avoidance efforts are greatly simplified by the selection of the science orbit and the strategy of not deploying the node spacecraft until after the hub spacecraft, with the nodes attached, achieves the science orbit. HelioSwarm does maneuver from the launch vehicle burn-out state to the science orbit via a series of phasing loops and post-lunar swing-by orbits which do cross the LEO and GEO altitudes [8]; however, the transfer trajectory has a minimum altitude of 1000 km and avoids the GEO belt entirely. The timing of the phasing loop maneuvers can be adjusted to mitigate collision risk per NASA's CARA Handbook, and the nodes are stowed in the hub throughout this mission phase leaving only one spacecraft to keep track of. All these factors contribute to a low risk of collision, and an expectation that the number of conjunction alerts that the team will have to respond to on a routine basis will be minimal, on the order of less than once per month. Intra-swarm collision avoidance is part of the design requirements, both for nominal relative orbits and possible drifting motion due to contingencies.

4.2 Mission Operations Process Scaling

Even with the mission concept simplifications explained in Section 4.1, the heritage MOS approach must scale to support swarm operations within the staffing constraints. Performing the MOS process cycle (Figure 9) for each of the nine spacecraft in a serial fashion would be prohibitive in both execution time and personnel resources. HelioSwarm's approach to scaling is to parallelize long duration sub-processes, either via software or virtualized hardware, such that they do not require 9x the processing time, and to select and deploy automation platforms to realize efficiency in the processes that must be run serially. The sections below describe HelioSwarm's current plan to apply these approaches to four of the key MOS sub-processes: orbit determination, maneuver planning, activity planning, sequencing and verification, and engineering data analysis.

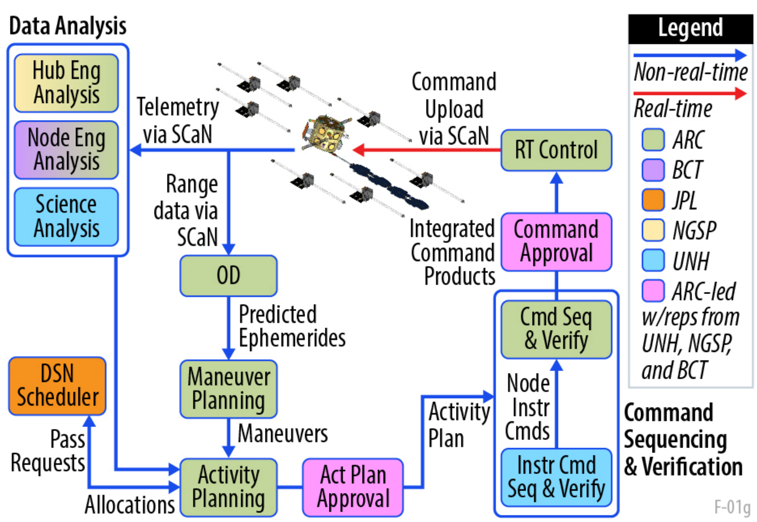

Fig. 9. Mission operations process flow showing the key MOS sub-processes and the information that is exchanged between them.

4.2.1 Orbit Determination

The orbit determination process will be scaled using a mixture of automation and parallelization. The Flight Dynamics System software automation platform will be configured to initiate the OD process as soon as tracking data arrives reducing the orbit analyst's role to monitoring, quality checking the results, tuning, and troubleshooting unexpected errors in the processing. Tracking data in this context comprises the hub tracking data as generated and recorded by the DSN (2-way Doppler and range) and the node-to-hub relative tracking data as generated and recorded by the hub. The relative tracking data is stored on the hub and brought to the ground during the 2-hr low data rate passes that are scheduled throughout the science orbit (see Figure 7). The automation platform will collect all this data in series of pre-processing steps, and then execute the main OD process with the pre-processed data. Because we cannot assume that the 2-hr passes will occur at advantageous times within the workday due to DSN scheduling contention, automating these steps to occur without an operator present will help to ensure that the data is processed as soon as it comes in, thereby reducing operational dead time.

In addition to the automated tasks, the process will also be parallelized in the sense the OD filter/smoother will process all tracking data in a single optimal sequential filter and generate an orbit solution for all spacecraft (hub and nodes) in the same run [11]. Executing in this way saves numerous input/output steps and is more computationally efficient. Preliminary OD studies have shown that this process is effective and not time prohibitive, executing in approximately two hours when run against simulated tracking data on a high-end personal laptop. Ansys Orbit Determination Toolkit (ODTK) was used as the OD engine in the preliminary study. Based on these early results we expect no issues meeting MOS cycle time due to OD processing in the operational environment.

4.2.2 Maneuver Planning

Even for single spacecraft missions, maneuver planning can be time consuming. The HS mission plan currently calls for each node to perform OTMs on a per orbit basis. Each OTM contains two distinct ΔV activities, resulting in a total of 16 ΔV activities to plan each orbit (~14 days). Scaling is obviously needed to keep maneuver planning activities to a single shift. HS's approach is three-fold: group both ΔV activities for a particular maneuver sequence into a single maneuver plan to minimize the number of maneuver planning cycles, utilize automation functionality within the Flight Dynamics System ground software, and maintain the approach that each node's maneuvers can be planned independently of the others.

Grouping the ΔV activities for a particular maneuver sequence results in a maximum of eight maneuver planning cycles per orbit (reduction from a possible 16). Each planning cycle contains overhead tasks such as coordination of the maneuver plan with other engineering activities, deconflicting with communications activities, exchanging products with other MOS functions, and documentation. Hence, keeping the number of cycle executions as low as possible is key to maintaining efficient operations.

Flight Dynamics System software automation for maneuver planning focuses on repeatability and improving operator efficiency. The software will always maintain the current definitive orbit solution from which to derive the initial conditions for the maneuver planning process, as well as maintain propulsion system modelling parameters for each spacecraft such that manual entry is not required. To increase repeatability and minimize operator mistakes, the software will allow the creation of maneuver planning templates and scripts to be executed for each node easily. In addition, the software will automatically produce and deliver products for consumption by other ground functions at the end of the process. This allows the orbit analyst to focus on quality checking rather than pointing-and-clicking and navigating directory structures. The placement of the OTMs, the processing of the OD, and the purpose and drivers for the OTMs are nearly identical from node to node, so the process lends itself well to this type of automation.

Ensuring that maneuver plans are independent between nodes allows for the process to be parallelized with minimal cost (additional workstation, cloud time, and/or software licenses) should the other scaling mechanisms not prove sufficient. For example, if the team realized during development that the orbit propagation step was taking longer than anticipated, they could decide to run the process for one set of nodes on one processor (or cloud instance), and another set on a second.

4.2.3 Activity Planning, Sequencing and Verification

Like the maneuver planning process, even for single spacecraft missions, activity planning, command sequencing and verification can be time consuming. HelioSwarm will keep the process time manageable by taking advantage of key simplifications and automation. The first key simplification is, as in maneuver planning, routine activity planning will apply to the swarm level. Each activity plan will include activities for all spacecraft, created in a single planning session, rather than a separate plan for each spacecraft created independently. Another simplification is the repetitive nature of the activities from orbit to orbit, and nearly identical from node to node. This allows for the development of re-usable activity plan templates that can be used to populate most of the plan, rather than inserting each activity one at a time. In addition, the repetitiveness of the operations from orbit-to-orbit allows for many of the command sequences to be pre-determined and encoded as command sequence templates, which can be automatically instantiated by a script using relevant data and timing from the plan as well as data from the Flight Dynamics System.

A similar template approach for activity planning and command sequencing was used on numerous missions including LADEE [12].

We have yet to identify any long running and non-parallelizable tasks which could significantly protract the command verification process. The simple Sun-pointing attitude profiles for the hub and nodes obviates the need for routine high-fidelity attitude simulation in hardware, which is typically one of the main drivers of verification time. Automated checks of static flight rules and constraints on the command sequences are expected to be sufficient to catch errors. As the concept of operations matures, the team will be wary of any routine activities that would require the need for hardware simulation, with the possibility of needing to add new steps to this streamlined approach. Additionally, the team will do a survey of available hardware emulation tools that would run faster than real-time that could be used as a mitigation if such requirements are identified.

4.2.4 Engineering Data Analysis

Despite the modest requirement for observatory data volume (~20 GByte / orbit, with most of that being science data), the processing, visualization and analysis of the engineering telemetry demands special consideration due to the multi-spacecraft nature of the mission. The mission sees automation as the main strategy to scale these tasks such that the operator's time is focused on high-level analysis and investigating anomalous data rather than mechanical steps such as navigating directory structures, pointing-and-clicking to build plots, and other lower-level tasks.

For the telemetry processing and rudimentary single-spacecraft visualization tasks HelioSwarm will use an open-source or GOTS/COTS command and telemetry system (C&T). The system will perform basic telemetry de-commutation, limit checking, and level-0 processing on each individual spacecraft's telemetry, all in the context of an automation platform that allows the user to run these tasks via scripting and/or a task scheduler. The mission will use such features to perform "lights out" operations for the routine 2-hour low-gain passes (schedule five times per orbit per Figure 7), and to automate the processing of the data returned during the 7-hour high-gain pass.

In addition to the requirement for automation, the project will consider other factors in choosing the operational C&T system. Systems that were built with multi-spacecraft systems in mind have clear benefits. Facilities for simplifying the management of the command and telemetry definitions/database and for the maintenance of spacecraft configuration parameters and on-board sequences across all nine spacecraft in one product will be highly valued. In terms of dealing with telemetry and commands across the hub and the nodes, while a single C&T system that handles both would offer benefits, the project does not consider it a requirement. The project will weigh the benefit of using a single product against other factors such as the potential amount of re-use with the spacecraft integration and test program, existing ground station compatibility, adaptation cost, and operator experience.

For more advanced visualization and analysis, the C&T system will be coupled with a plotting and trending system. Required features of the plotting and trending system will be an ability produce plots comparing data between multiple spacecrafts (e.g. plot battery voltage for all spacecraft on the same axis), an ability to compare telemetry trends of the same telemetry across different spacecraft (e.g. the CPU temperature on node 3 and node 4 over the same period of time), and a facility for publishing results to web-based platforms to allow analysis by remote operators. Like with the C&T system, automation features within the plotting & trending system are paramount. The system must allow for automatic production of a configurable set of plots and analysis each time data is received from the swarm. This allows the operator to focus on quality checking results, identifying out-of-family data, and developing responses rather than the mechanical process of creating plots and running trend analysis.

For the selection of both the C&T system and the plotting and trending system, the project will favor those with the proven ability to run in a virtualized and/or cloud-based environment. Having products that readily run in such environments will facilitate the task of parallelizing or scaling up processing power or memory should the need arise.

4.3 Ground Data System Software Development Approach

As a NASA mission, HelioSwarm will follow the NASA standard software development lifecycle, which includes requirements definition, architecture development, design, implementation, and test. HelioSwarm's specific implementation of these procedural requirements is beyond the scope of this paper. However, several key points relevant to how the team intends to ensure that the MOS/GDS process is executed with sufficient efficiency are summarized here.

With respect to the MOS/GDS requirements definition, HelioSwarm will start with the MOS process flow diagram (Figure 9) and operational timeline (Figure 7) to structure the process execution timing requirements. The durations in the operational timeline diagram indicate the Phase A-level allocation of the week-long MOS process execution time to the key MOS-subprocesses. The allocation is based on the team's previous mission experience, existing GOTS/COTS GDS capabilities and the expected efficiency gains from scaling strategies explained in

Section 4.3. Once in Phase B, the MOS systems engineer will take the time allocation and levy a process execution requirement on the corresponding GDS tool or tools. These requirements will have the form of: "The Flight Dynamics System shall support the generation of two routine maneuver plans in one 8-hour shift with one full-time Orbit Analyst on a dedicated workstation". In this form, the "Maneuver Planning" process is the MOS sub-process in question (akin to the purple bar labeled "Maneuver Planning for days 22-36" in Figure 7), and the allocation is to the Flight Dynamics System (FDS) because it is the GDS sub-system that the staff will use to execute the process, and the execution time is cast as number of hours or days assuming a particular number of staff to execute the process.

It is important to note what these process execution requirements do not specify – namely, a level of computing power and/or speed. That omission is on purpose to allow flexibility in the overall design of the system, which is especially important for the scaling of the GDS. If, for example, the team determines that the FDS maneuver planning procedure takes one hour to run, while its allocated time is only 30 minutes, then scaling might include the purchase of an additional software license and/or an additional workstation instance (either physical or in the cloud), such that two FDS procedure can run in parallel. This concept is supported by features of the heritage FDS and allows for optimization of operations cost. Later in the design phase, the systems engineer could shift the allocations based on performance estimates. For example, the team may discover that orbit determination or mission planning requires less time than currently allocated, and hence the allocation for maneuver planning can be increased. In summary, the MOS systems engineer has numerous knobs to turn to optimize the efficiency as the design matures.

With respect to the design, implementation, and testing phases, HelioSwarm will use a mixture of predictive (e.g. "waterfall") and adaptive (e.g. "Agile") methodologies. The former will be used for processes and tools with more heritage and where the multi-spacecraft aspects of HelioSwarm have limited impact their requirements. The C&T system used for monitor and control of the hub would fall in this category. Conversely, for those tools and processes with more uncertainty and those that require more scaling, the team will lean towards an adaptive approach, using short and frequent development / test cycles involving the end user to gain feedback and adjust the lower-level requirements as necessary. The activity planning system which is required to accommodate activities for all swarm elements and the plotting and trending system which is required to integrate data from across the swarm are two examples of tools that will be developed (or customized depending on maturity) using the adaptive approach. Doing so will help ensure that the tools truly meet the needs of the user and the process execution timeline.

5. Conclusion and looking forward

In this paper we introduced the mission operations concept and the beginnings of the MOS and GDS design for the HelioSwarm mission. We summarized the mission's approach to developing a system with a high enough operational efficiency to allow operations with a moderately sized operations team through a focus on simplicity and through scaling the operations tools and processes with parallelization and automation. We expect this approach to guide the development of the MOS and GDS as the project advances into its later phases even when driving requirements evolve over time, as they always do. We hope to report on future advancements with more detail as the mission matures, especially as they relate to the application of spacecraft swarms to answer fundamental science questions.

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