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Active Swarm Resiliency in the HelioSwarm Mission

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ABSTRACT

Designed to observe plasma turbulence dynamics in solar wind over a distributed volume of space, the HelioSwarm mission comprises a primary chief spacecraft and eight smaller deputy satellites in uniquely assigned "loops" of periodic relative motion in a P/2 lunar resonant orbit. If one or more deputies fail, this multi-satellite architecture facilitates resiliency for science goals through repositioning of satellites to contingency loops. This strategy of Active Swarm Resiliency mitigates risk by modeling quantitative results ahead of time for mission operators to make informed decisions. Responsive actions meet minimum science objectives based on past and predicted system performance, an approach with applications to future missions with similar architecture and requirements.

INTRODUCTION

Swarms are increasingly becoming a popular mission concept for applications involving small satellites. As opposed to a constellation where member spacecraft are widely distributed along either the same or multiple different orbits such as geosynchronous GPS satellites or SpaceX's Starlink internet network, a swarm consists of multiple satellites in close proximity to one another relative to the scale of their similar orbits and operating together as a single entity.[1] Through leveraging the lower cost and complexity of smaller satellites, swarms allow for more points of contact for mission operators in collecting scientific data or communications while also enabling a mission to continue beyond the failure of an individual member of the swarm. Current examples include ESA's Swarm and NASA's Magnetospheric Multiscale (MMS) mission, each consisting of three and four satellites respectively with the shared goal of studying the Earth's magnetosphere via measurements from multiple points within a three-dimensional volume simultaneously. The potential benefits of multi-satellite measurements are clearly intriguing for mission designers, but the increasing complexity as the number of satellites within a swarm rises requires careful planning to fully utilize these advantages.

The concept of swarm management is already frequently employed in terrestrial applications such as with Unmanned Aerial Vehicles (UAVs). Large UAV swarms have been employed in aerial photography, surveying, meteorology, military deployment, and even entertainment purposes in light shows. In some cases, the additional vehicles simply provide redundancy in the event of any individual failure, but other applications may require the swarm to modify its behavior or mission following the loss of swarm members. For UAVs traveling in close proximity to one another or environmental obstacles, recovery operations necessitate action faster than the ability of human operators on the ground and require algorithmic decision-making and autonomous control. Along these lines, work by Wubben et al. developed algorithms for a resilient UAV swarm to reconfigure itself following the loss of individual members or a communications dropout while a research group led by Chen used a Swarm Intelligence-based Damage-Resilient (SIDR) mechanism to similarly reorganize a severely damaged swarm of UAVs back into a coherent network.[2,3]

Compared to terrestrial applications, swarms of orbiting spacecraft typically offer mission operators more time to respond in the event of a malfunction, but also come with their own unique set of challenges in adjusting trajectories for reconfiguration that must be addressed. Much of the study in this area so far has focused on constellations, such as research led by Wagner and Azza both employing genetic algorithms to reconfigure a group of satellites following an individual failure to balance fuel efficiency and observation time.[4,5] However, the research group headed by Izzo developed a technique they called equilibrium shaping to determine optimal positioning for swarm members in the form of velocity vectors and then employed autonomous control to achieve these vectors.[6] More recently, Chen et al. used a surrogate model to approach the problem of satellite swarm reconfiguration.[7]

In contrast to these previous efforts, the HelioSwarm project team at NASA Ames Research Center has developed a novel methodology referred to as Active Swarm Resiliency that keeps mission operators in the decision-making process and provides them with a quantitative analysis for a broad range of off-nominal scenarios before they occur. In operational applications, the process incorporates the current status of the mission at the time of a spacecraft malfunction to clearly visualize how different recovery responses will affect future progress towards achieving science goals at a glance. This paper first provides background on HelioSwarm and the plasma physics science goals that drive its design before describing the basics of swarm reconfiguration procedure for the mission and the constraints and assumptions made in the analysis. An overview of the Active Swarm Resiliency methodology is then given before a demonstration of how it is applied to a specific failure scenario using an example case.

HELIOSWARM BACKGROUND

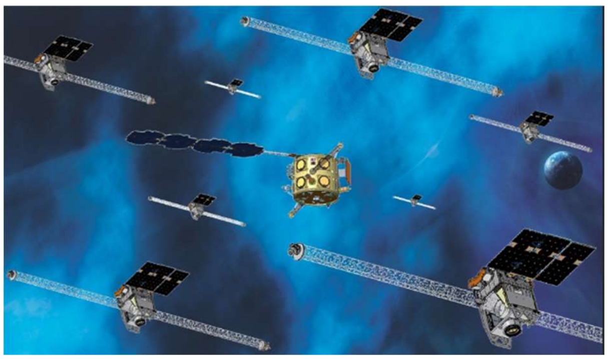

Figure 1: HelioSwarm Hub and Nodes in Turbulent Plasma Environment

HelioSwarm Mission Architecture and Science Goals

HelioSwarm is an upcoming Medium-Class Explorer (MIDEX) mission recently selected by NASA to study the poorly understood phenomenon of plasma turbulence dynamics through observations of the solar wind.[8] Currently in the Phase B prep stage, HelioSwarm is planned to launch in early 2029 to an elliptical High Earth Orbit (HEO) in a P/2 resonance with the Moon to yield an orbital period of roughly two weeks. The hub-and-spoke communications topology seen in Figure 1 consists of a primary chief satellite that releases eight deputy spacecraft upon reaching the science orbit to collect measurements and relay the gathered data back to the hub. Following separation, each of these identical deputies insert into unique periodic relative motion with respect to the hub (referred to from here on as a loop), viewed in the local Velocity-Normal-Conormal (VNC) coordinate frame in Figure 2. These loops are then carefully maintained using low magnitude delta-v maneuvers throughout the mission while the hub undergoes no additional burns after arriving in the science orbit.[9] This pre-planned swarm configuration allows for observation of plasma interactions from multiple points simultaneously across a variety of

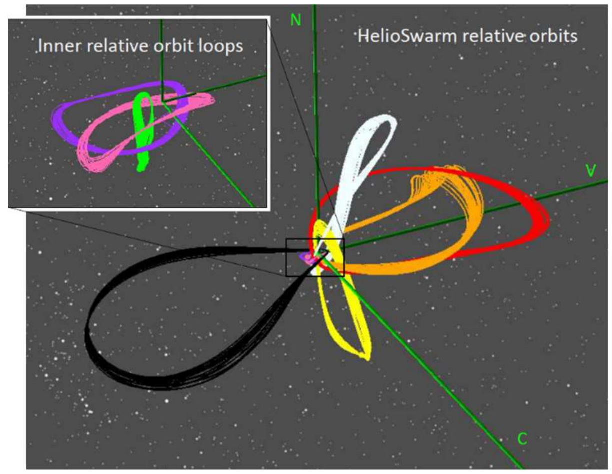

Figure 2: HelioSwarm Nodes in Nominal Loops in Hub VNC Frame

distance scales, including the ion-kinetic range on the order of approximately 100 km to the magnetohydrodynamic (MHD) range around 1200 km as well as the transition scale between them.

Both the nodes and the hub are equipped with a common suite of instruments to take measurements from their particular location in space, including boom-mounted fluxgate and search-coil magnetometers to record the strength of the local magnetic field as well as Faraday cup sensors for characterizing ionic velocity distribution and flow angle.[10] The hub alone also carries an additional ion-electrostatic analyzer instrument to measure proton and alpha plasma parameters. At high orbital altitudes near apogee, swarm members reach the greatest relative distance from the hub to form favorable geometric configurations for scientific observations. Near perigee, the node spacecraft return to their closest relative position at slightly offset times to facilitate data transmission to the hub for downlink to a ground station while still maintaining minimum safe distances.

Solar Wind Regimes

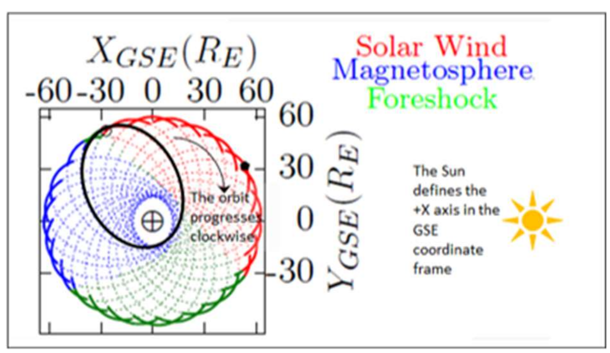

Figure 3: Solar Wind Activity Regions Explored by HelioSwarm (Courtesy of Kristopher Klein)

HelioSwarm's science orbit will carry the swarm through distinct regions of solar wind activity that are divided into three regimes as seen in Figure 3. The area of pristine solar wind that has yet to contact the Earth's magnetic field lies roughly between the Earth and the Sun. Once solar wind particles reach the magnetosphere, regions of strongly driven turbulence are formed through their interaction both directly within the magnetosphere's wake, as well as an ion foreshock region caused by the Earth as it travels around the Sun. The portion of HelioSwarm's orbit close to apogee where the primary science data collection gradually cycles through all three regimes over its yearlong primary mission since the orientation of the orbit remains approximately fixed in an inertial frame while the Earth-Sun vector rotates around it. Gathering sufficient observation hours from both the pristine solar wind and the combined strongly driven turbulence regions are essential to meeting HelioSwarm's science objectives and define two types of mission requirements.

HelioSwarm Geometric Configurations

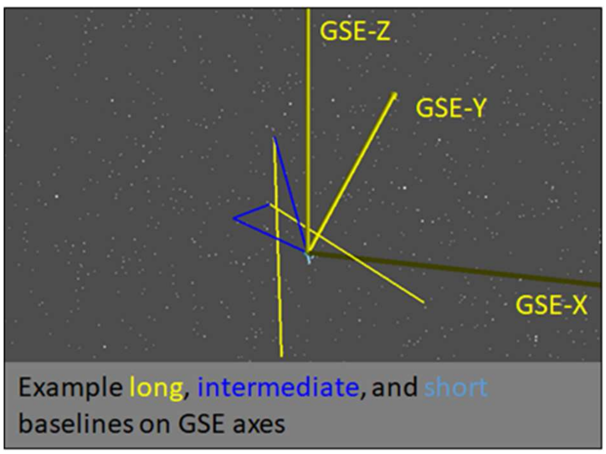

Figure 4: HelioSwarm 3-D Baseline Geometry

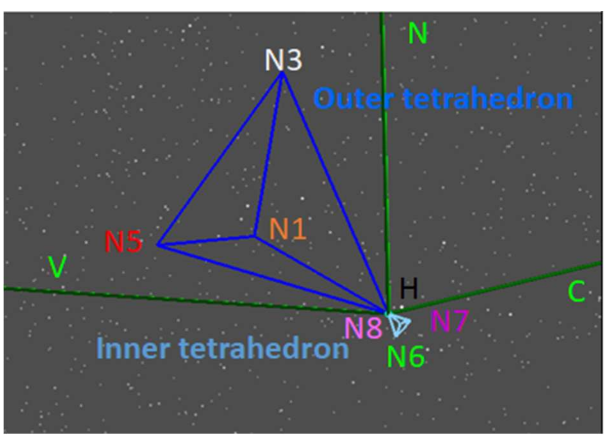

Figure 5: HelioSwarm Tetrahedron Geometry

While the distributed architecture of HelioSwarm is designed for simultaneous data collection from multiple points within the solar wind, the quality of science gathered strongly depends on the relative position of each spacecraft within the swarm. Two different types of geometric configurations form with the hub and nodes. The simplest of these are 3-D baselines (Figure 4), or the collection of all possible lines that can be drawn between any two spacecraft. These baselines should be arranged to lie both in parallel and transverse to the direction of the flow of solar wind. Additionally, tetrahedral formations (Figure 5) comprised of four spacecraft are also required. Two simultaneous tetrahedra of different scales with desired planarity and elongation values must be present in order to capture the cascade of energy across scales in plasma turbulence. When the swarm formation meets at least one of these configurations, that time counts toward required observation hours of the corresponding solar wind regime that the swarm currently occupies.

SWARM RECONFIGURATION PROBLEM

Redundancy, Robustness, and Resiliency

Redundancy, robustness, and resiliency are terms that are frequently used interchangeably in the common vernacular but have more precise and mutually exclusive definitions in engineering parlance when applied to complex systems like HelioSwarm.[11] Employing multiple identical components that fulfill the same function in a system to allow for another to seamlessly take over in the event of a single failure characterizes redundancy. Robustness refers to the capability to withstand failures while successfully maintaining nominal operations, often quantified as margin on requirements. Finally, resiliency is the ability of a system to react to and recover from a degraded or damaged state with little to no effect on its dynamic stability.[12] Despite HelioSwarm nodes being physically identical, each one fulfills a unique role in the swarm to achieve specific assigned 3-D baselines and tetrahedral arrangements As a result no true redundancy exists at the highest system level since no node is completely replaceable, although there are redundant pairwise combinations that meet the same 3-D baseline requirement. Mission robustness is built into the concept of operations, such as the anticipated hours of science data gathered in a one-year nominal mission profile allowing for plenty of margin above minimum baseline and threshold values to achieve science goals as well as the possibility of an extended mission if these hours end up falling short following a malfunction. However, the scope of this paper concerns the Active Swarm Resiliency approach employed by HelioSwarm.

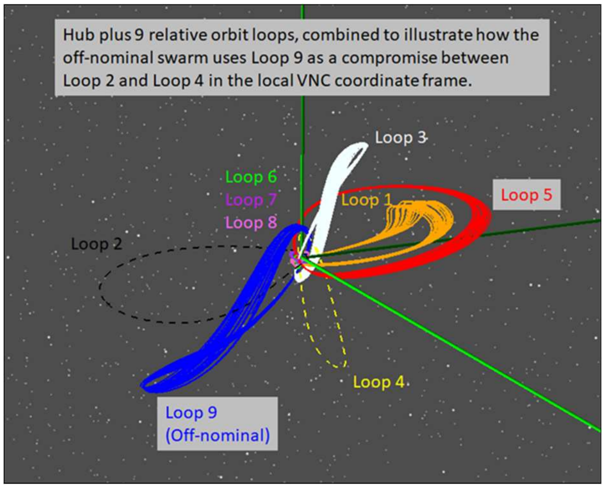

Figure 6: Contingency Loop 9 (in Blue) as Hybrid of Loop 2 and Loop 4

HelioSwarm Reconfiguration: A Fault Management Approach

In addition to distributed data points providing coverage of an extended volume of the solar wind, the number of deputy satellites also offers mitigation options if one or more are unable to collect or relay measurements in the event of a serious malfunction. When a node is disabled, the relative motion of another satellite can be altered to create alternative geometries for high quality science measurements. Repositioning sets the responding spacecraft onto a pre-planned contingency loop designed for the best possible coverage of both the failed node and the one moved to replace it as seen in Figure 6. While the orbital mechanics involved in the repositioning of node spacecraft are beyond the scope of this investigation, this process is detailed in an upcoming paper by Levinson-Muth included in the reference section. [13] Selecting the best course of action in the event of a malfunction greatly depends on which deputy satellite ceases functioning and when in the mission the failure occurs. It is also possible to reposition nodes within the swarm multiple times after a node failure if sufficient propellant remains, as different configurations may be more ideal for achieving tetrahedral geometry but not for 3-D baselines and vice versa. The potential loss of multiple nodes also adds additional complexity to planning for contingencies.

To prepare responses that account for such a wide range of failure scenarios, an approach using the systems engineering method of fault management can address this problem of combinatorial expansion. Defined by Johnson as "the operational capability of a system to contain, prevent, detect, isolate, diagnose, respond to and recover from conditions that may interfere with nominal mission operations" including the "processes to analyze, specify, design, verify and validate such capability", fault management typically applies to a single system comprised of physically interconnected components.[14] However, the specific internal issues that might potentially disable one of the eight deputy satellites or the hub in conventional fault management are beyond the scope of the Active Swarm Resilience methodology detailed here. The entire distributed swarm is instead treated as its own singular assembly, with the hub and nodes becoming the discrete components that make up the unified system. The desired goal of this analysis is to map out potential failure configurations prior to the mission and provide the operations team with an additional decision-making resource to determine the best course of action given the current mission status and cumulative hours of science data collected at the time of failure.

Swarm Reconfiguration Constraints & Assumptions

For the current scope and maturity of Active Swarm Resiliency, there are several constraints and assumptions that must be considered before exploring the method itself. First, members of the swarm are assumed to be in a binary state of either operational or failed. Note that at present this simplification neglects partial or gradual failures such as the loss of a single instrument while others in the suite continue collecting data or a propulsion or attitude control system malfunction that causes a node to slowly drift from its assigned loop due to an inability to conduct maintenance burns. However, this also includes the possibility of a node being restored to full function later through intervention from the ground.

Following a serious spacecraft malfunction that renders it unable to collect or relay data, mission operators will most likely try multiple troubleshooting attempts to bring it back online. If these actions are unsuccessful and the satellite is declared inoperable, the next step is to determine if moving a node to a contingency loop is advisable at the current mission state. The response process takes time and may leave the swarm unable to take effective science measurements while it remains in a degraded state. Once ground operators decide to move a node to a contingency loop, an additional time cost is a factor as the maneuvering satellites move between pre-determined loops. While the total duration of these response activities varies depending on the timing and which loops are involved, a typical delay is around three orbital cycles total for the first failure with subsequent actions for a second loss taking only two as a result of learned experience. This period is also treated as a variable in the Active Swarm Resiliency process and multiple durations are used in the full study. Note that depending on which node fails it may be possible for the swarm to form favorable geometries during deliberation and repositioning to accrue additional science hours, but this is discounted to simplify analysis which results in a more conservative estimate.

From observing Figure 3, it is evident that the pristine solar wind regime of plasma turbulence covers the smallest volume of the regimes explored by HelioSwarm and is correspondingly the most challenging area in which to record sufficient observational hours. To compensate for the shorter duration in pristine solar wind, the current mission design establishes the science orbit such that the apogee passage through the pristine region occurs early in the science phase timeline. The first few months of observations are then spent in this regime as the line of apsides gradually undergoes precession in the rotating Earth-Moon frame. This has the two-fold effect of both gathering data from the pristine solar wind regime when HelioSwarm has the highest probability of full functionality and also allowing for this region to be the first to be revisited after the initial one-year mission if an extension is needed to meet minimum science requirements. While ensuring an overall higher chance of success, this strategy also leaves the mission particularly vulnerable to losing a swarm member early in its operation.

Finally, there are several extreme failure scenarios beyond the ability of Active Swarm Resiliency to recover. The complete loss of the hub satellite is an automatic mission failure since it is solely responsible for ground communications with Earth. However, it is possible for the hub to lose one or more of its onboard scientific instruments while the rest of the satellite remains functional, a unique contingency case with its own reconfiguration plan. The failure of three or more nodes also leaves the swarm unable to form the necessary number of tetrahedra since a minimum of six are required, but some lower threshold values of data collection might remain in reach.

METHODOLOGY

Generating Position Data

The first step in the process of Active Swarm Resiliency is to predict the anticipated positions of the hub spacecraft and its nodes over its year-long science mission, both for nominal operations as well as motion in contingency loops. This input is necessary to determine when desired geometrical configurations are attained to estimate total accrued hours of observational data. High-fidelity trajectory simulations generate these position estimates using the space mission analysis software Systems Tool Kit (STK) from AGI. With provided initial orbital conditions and states, STK produces output for the duration of the science mission calculated using an ephemeris model that includes perturbation effects using a high-fidelity propagator accounting for J2, luni-solar gravity, and solar radiation pressure (SRP). Each node performs maneuvers to maintain its relative loop and STK models the resulting orbit motion, outputting a series of position states at set time intervals.

Vector Analysis Tool

The HelioSwarm-specific Vector Analysis Tool (VAT) takes the state vector for all members of the swarm at hourly timesteps and identifies if the geometric configuration at that time satisfies the requirements for either 3-D baselines or tetrahedra. Baselines should exist both transverse and parallel to the direction of solar wind while the tetrahedra are evaluated based on the desired properties of low planarity and elongation values. To ensure that data is collected on a multi-scale basis as necessitated by the science mission guidelines, the size of the largest of the tetrahedra must also be at least three times greater than the smallest. If these requirements are satisfied based on the previously generated position data for the swarm, the VAT will count the hours toward the bare minimum threshold of desired hours and the larger number of baseline hours. These results are broken down by each of the two previously defined spatial regimes and geometric configurations. Through this method, a quantitative value can be assigned to a given scenario that aids immensely in evaluating between different response options.

The VAT interface allows for a user to select individual nodes to remove from the swarm to simulate a malfunction and when in the mission this event occurs using the graphical interface, analogous to injecting a fault in traditional fault management modeling. The timeframe for a node failure is demarcated into the discrete numbered science orbit cycle, or approximately two-week blocks. Additionally, the user can specify a second node to be removed from the swarm to represent a multi-failure scenario at its own unique time. For eight nodes and the hub's instruments, this creates a total of nine unique off-nominal single failure configurations and seventy-two dual failure configurations. This allows for thousands of different potential scenarios once the orbital cycle in which each node failure occurs is specified. The VAT can iteratively process multiple scenarios, allowing for the compilation of a database covering failure cases for all unique pairs of two nodes at any orbit cycle during the primary mission with the additional option of evaluating the effects of an extended mission. The results of the VAT output are concisely displayed in a figure referred to as a summary grid for each combination of two nodes, allowing mission operators to see the effects of their combined failure for any orbital cycle during the year-long science mission.

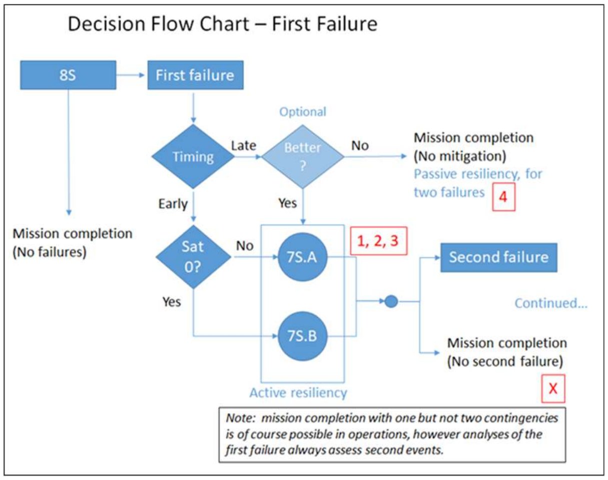

Figure 7: Flowchart of Responses for First Contingency Event

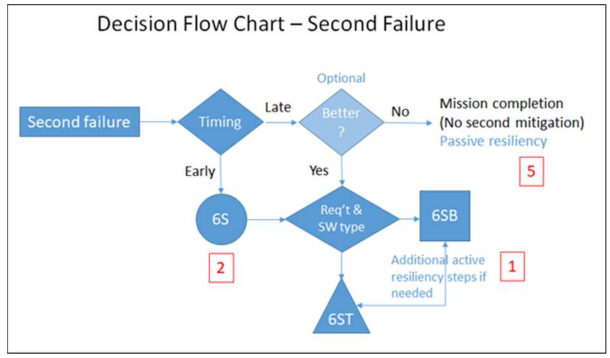

Figure 8: Flowchart of Responses for Second Contingency Event

ACTIVE SWARM RESILIENCY: EXAMPLE SCENARIO

Example Scenario Description

The goal of active resiliency planning is to provide ground operators with predicted performance outcomes in off-nominal swarm configurations. The generalized sequence of fallback options appears in the diagram in Figure 7, with shorthand annotations for decisions and outcomes explained below.

Off-nominal planning for HelioSwarm includes pre-determined swarm formations, designated "#S" for the swarm comprising the hub as "Sat0" (or alternate occupancy at the local origin) plus the identified number of free flying nodes. For simplicity, the decision flow's dependence on the timing of the first failure uses only early and late timeframes within the mission duration, with the milestone defining them as a variable calculated in pre-mission analysis of each combination of failed swarm members. The robustness of the nominal mission design leaves a significant portion of the Science Phase duration as margin, when optional repositioning can improve the science return but is not necessary for meeting requirements. This leaves active resiliency to the discretion of the project team. Loss of the hub's instrument suite has a unique mitigation, designated as "7S.B," which is omitted from the examples here. Decision logic in response to the first failure includes predictions of the effects of second failure cases; no analysis cases assume only one failure will occur, though of course it would be advantageous to the mission not to have multiple contingencies. While further loss of swarm members is theoretically possible, HelioSwarm mission requirements apply to the failure of only two swarm members. An example mission scenario depicted in Figure 8 illustrates the decision flow for two failed nodes with specifics for the numbered outcomes.

Each analysis case for a second failure includes the model of a preceding failure, leading to multiple combinations of outcomes. The standardized swarm configurations in response to the first failure, 7S.A and 7S.B, provide a known starting formation for mitigating the second contingency. As in Figure 7, here part two of the flowchart simplifies the timing of the second contingency into categories of early and late; with some mitigations being optional to improve overall performance above requirements.

Figure 8 includes an element of complexity not needed for the first contingency. With hub plus six nodes, it is not possible to meet both geometric requirements simultaneously; operators can reconfigure to 6SB for 3D Baselines or 6ST for tetrahedral requirements. Later additional maneuvers can convert between 6S types for coverage of both solar wind regions, sometimes involving an extension of the mission science phase duration beyond the nominal value of one year.

First Failure Event

An example scenario for failures of Node 1 and Node 7 from the outer and inner tetrahedra illustrates how the supporting analyses for the flowchart of events provide input to operational procedures. Upon the failure of Node 1, the following options are available for operators to consider (Table 1).

Table 1: First Failure Event, Node 1 Becomes Inactive

Timing of Node 1 Failure	Outcome Type
Orbit cycle 1 through orbit cycle 8	Outcome type 1, 2, or 5 (depends on future events)
Orbit cycle 9 through orbit cycle 12	Outcome type 3
Orbit cycle 13 or later	Outcome type 4: response is optional

Response for Outcome Type 1, 2, 4, and 5

- Assume one orbit cycle for diagnosis and decision making on the ground
- Allow two orbit cycles for repositioning maneuvers
  - Reconfigure to 7S.A
  - Maneuver Satellite 2 to occupy Loop 9
  - Maneuver Satellite 4 to replace the inactive spacecraft in Loop 1

Response for Outcome Type 3

- If ground activities and repositioning in orbit can complete in two orbit cycles total, then formation 7S.A with the same next two steps will create robustness to a second failure
  - Maneuver Satellite 2 to occupy Loop 9 (as with other outcome types)
  - Maneuver Satellite 4 to Loop 1 (as with other outcome types)

Second Failure Event

Given that Node 1 has failed and its mitigation has begun or completed, Node 7 now becomes inactive yielding the following options (Table 2). (Similar logic for different preceding conditions not included in this example.)

Table 2: Second Failure Event, Node 7 Becomes Inactive

Timing of Node 7 Failure (After Node 1 failed)	Outcome Type
Orbit cycle 1 through orbit cycle 11	Outcome type 1, 6SB and 6ST needed
Orbit cycle 12 or later	Outcome type 2, 6SB will be sufficient

Response for Outcome Type 1

- Reconfiguring to 6SB in support of 3-D baselines can complete from one orbit cycle to the next
  - Maneuver Satellite 3 from Loop 3 to Loop 11
- Reconfiguration in support of tetrahedral requirements will call for a four-month extension to the mission duration
  - In orbit cycle 24, Satellite 2 (now in Loop 9 after the first contingency response) maneuvers to replace Node 7 in Loop 7 in the 6ST formation
  - Also in cycle 24, Satellite 3 returns to Loop 3

Response for Outcome Type 2

- Reconfiguration in support of 3-D baselines can complete from one orbit cycle to the next
  - Maneuver Satellite 3 from Loop 3 to Loop 11
  - Tetrahedral requirements meet full success with the response to the first failure (Node 1)

Foreknowledge of when in the course of the mission duration each type of requirement will reach successful performance relies on simulating the changes to the swarm configuration with event timing as an independent variable. The initial conditions of the science orbit dictate how long it will take to accumulate required hours. Case studies here use the current reference design for the HelioSwarm science orbit.

Supporting Analysis

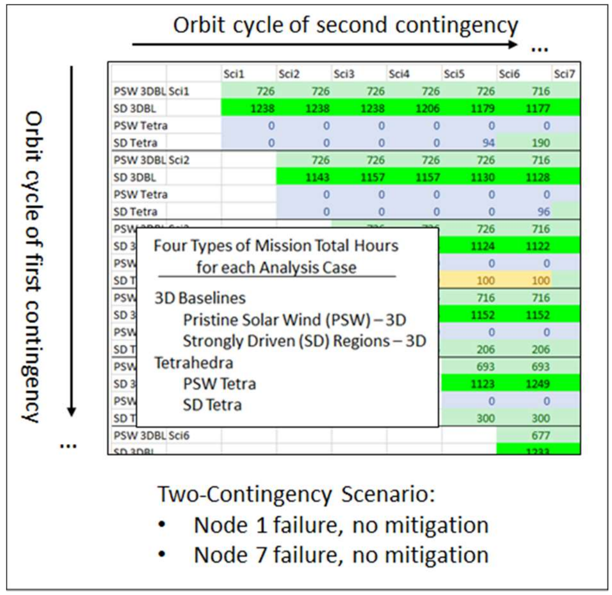

Figure 9: Partial Grid Example with Color-Coded Science Hours Accrued for Each Category

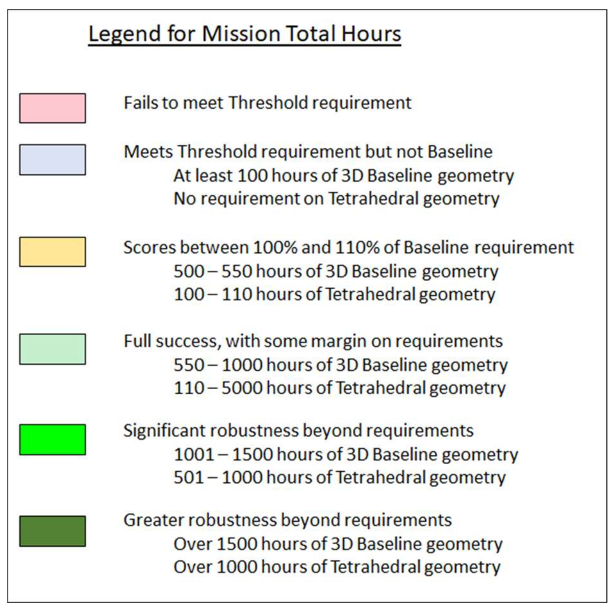

Figure 10: Color Legend for Summary Grids

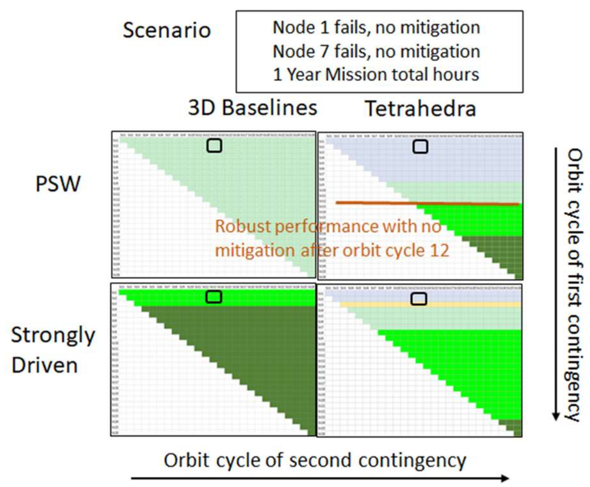

Figure 11: Timing Dependency for Example Scenario

Because the timing of contingency occurrences is a major factor in the outcomes and responses, analyses of two-contingency cases show results in a summary grid with two time axes, one for each satellite. The VAT models the presence or absence of each swarm member in every orbit cycle and computes the end of mission total hours in each requirement category. An example of a partial grid is shown in Figure 9 displaying mission total hours in the four categories of requirements for each timing combination of Node 1 failure (no mitigation), followed by Node 7 failure (no mitigation). Figure 10 gives the color key for total mission performance.

For visual summaries of performance across the full set of timing combinations, color codes compare mission totals to the required hours in each category of requirements. Shades of green highlight where robustness in one category may indicate where alternative approaches can improve performance in other cases. The other colors indicate marginal, partial success, and unsuccessful final results.

Predictions of off-nominal outcomes occur long in advance of flight operations. The analysis for each failure combination begins with the least activity in response and builds up options until full success is possible in any eventuality. Figure 11 provides a visual summary of timing dependency for results in four requirements categories. This shows that if the mission passes orbit cycle 12 without contingencies (in this case study), then full success is possible without mitigating action. Since the milestone in the progress of the mission designates the timing of the first contingency, the results below the cutoff line in Figure 11 represent outcome type 4 in the flowchart. The highlighted case for Node 1 failure on orbit cycle 2 and Node 7 failure on orbit cycle 13 is useful in comparing performance details.

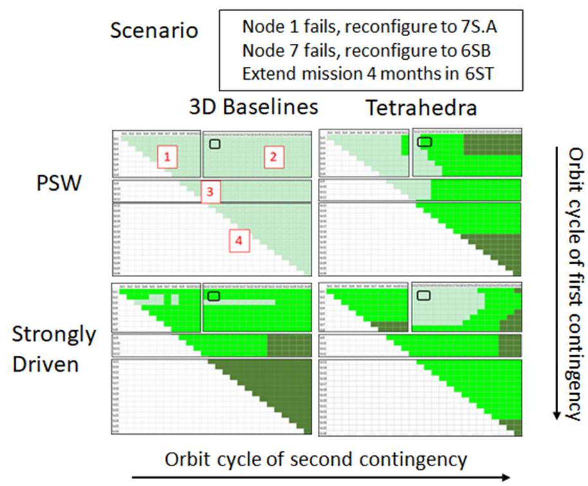

Figure 12: Outcome Performance Summaries

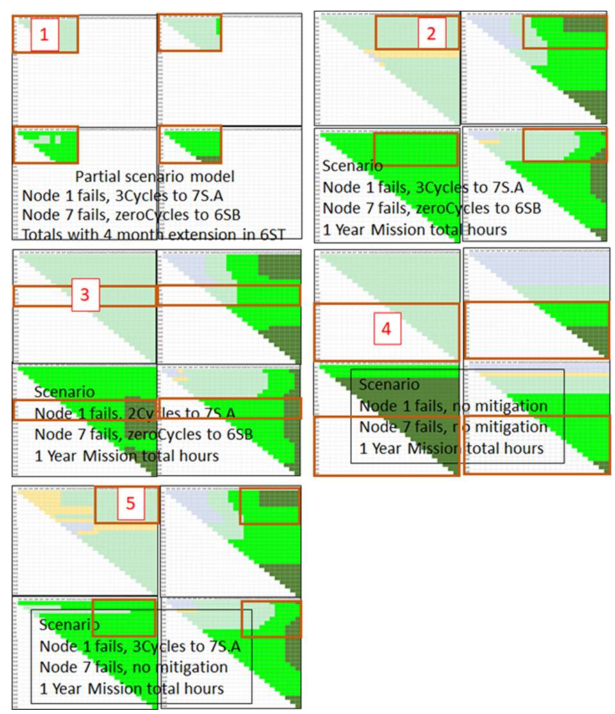

Figure 13: Visual Summaries for All Outcome Types

For contingency scenarios that begin earlier than orbit cycle 13, repositioning some of the remaining nodes will create active resiliency. Figure 12 compiles the visual performance summaries for the outcome types in the decision flow chart. Cases losing two satellites early in the mission also include a non-maneuvering mitigation of a second passage through the pristine solar wind by extending the mission duration by 4 months.

Visual summaries for all outcome types included in the flowchart for the Node 1 and Node 7 case study appear in miniature in Figure 13. Automated iterative computations in the VAT enable mission planners to

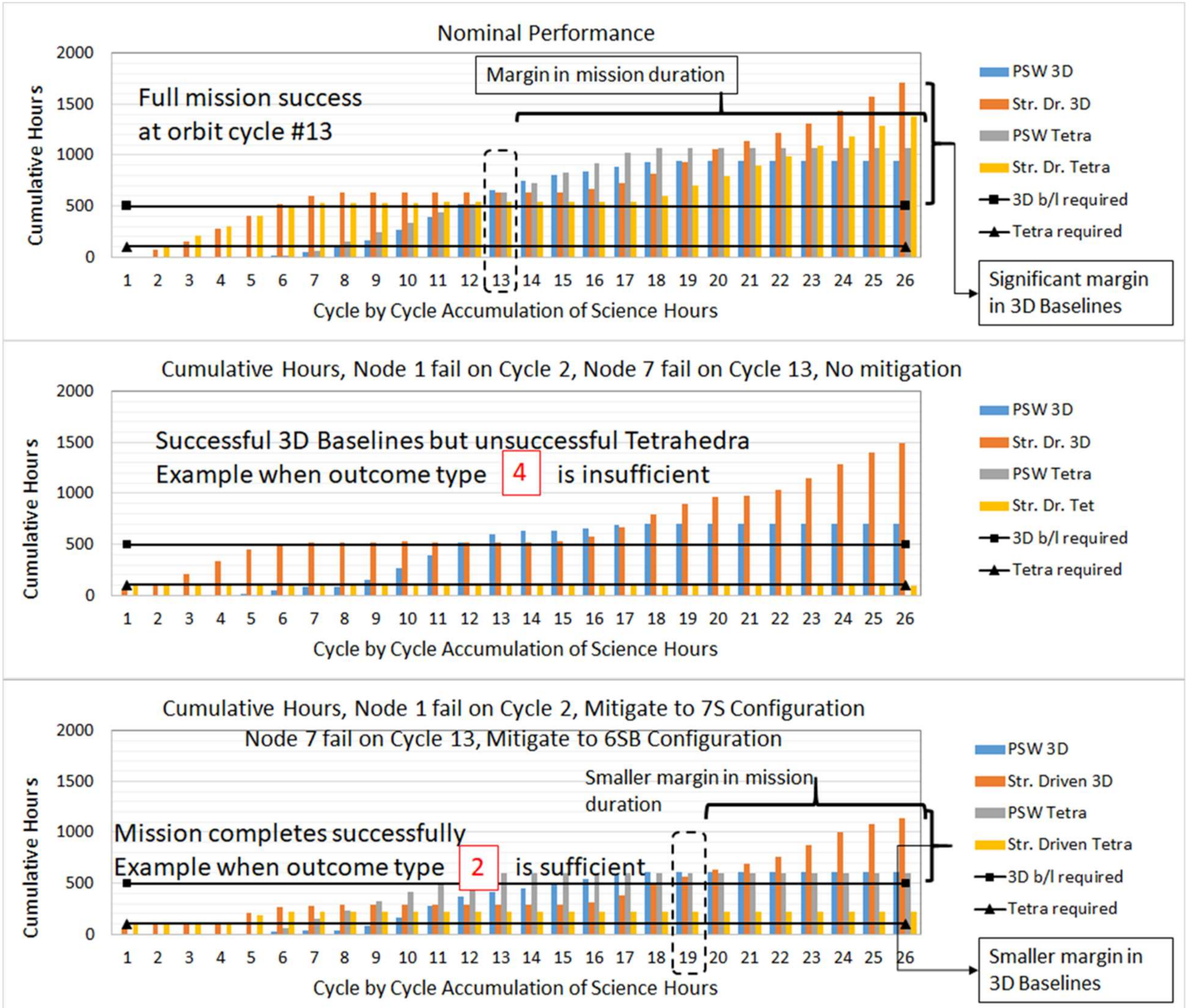

Figure 14: Bar Plots Depicting Accumulation of Science Hours by Cycle for Various Response Options

select among response options for any combination of two-contingency timing.

Details of an example two-failure case are now examined. For a contingency on Node 1 in orbit cycle 2, followed later by a contingency on Node 7 in orbit cycle 13, Figure 14 compares the accumulation of science hours in four categories. The nominal case has significant margin in mission duration, allowing outcome type 4, no mitigations, to be sufficient for failures late in the mission. The second graph illustrates why outcome type 4 is insufficient for the contingency timing in the example case: 3-D baseline requirements are successful but there are not enough hours in the tetrahedral configuration. The third detail graph shows the accumulation of science hours with outcome 2 applied to the example event sequence. The mission uses more duration and reaches lower overall totals but still achieves full success.

CONCLUSION

The innovative use of Active Swarm Resiliency provides HelioSwarm with advantages beyond the additive performance of multiple spacecraft as demonstrated here in an example case study. If a fault management diagnosis leads mission operators to conclude that a swarm member is no longer contributing to the collection of science data, there is a new level of responses available in repositioning active swarm members to fulfill the geometric requirements in alternative configurations.

However, reconfiguring the swarm is not without cost. There is a multivariate analysis space of possible outcomes to assess, including a strong dependency on the initial conditions of the science orbit based on launch dates and insertion parameters. In operations, the time spent maneuvering depends on the propulsion capability of the spacecraft but is likely to create intervals when some satellites are temporarily poorly positioned for meeting geometric requirements. The repositioning maneuvers are generally affordable in terms of delta-v budget at costs lower than 5 m/s but must be included for the mission to have Active Swarm Resiliency as a potential option.

Redundancy, robustness, and resiliency work together to increase chances of mission success in off-nominal situations. While avoiding duplication of specific assigned roles, the flexibility of swarm configurations offers alternative ways to meet requirements such as functional redundancy. Robustness in performance above required levels provides a conceptually fluid resource for mission planners to improve performance in weak areas by allowing reduced results in overperforming cases. Depending on the timing of events, passive resiliency may allow the swarm as a system to perform adequately in a degraded state. However, active resiliency is a mission enhancing capability that can deliver full success in many circumstances which would otherwise compromise mission objectives. With simulations and the ability to look up predicted outcomes, mission operators have a highly effective new approach to contingency mitigation.

Active Swarm Resiliency is a novel property of multi-satellite missions that stands to reduce risk and improve performance. As swarm-type concepts become more common and increasingly ambitious in scope, this technique has high potential for applications beyond HelioSwarm to assist in achieving complex science goals.

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REFERENCES

1. Farrag, A. and S. Othman, T. Mahmoud, A. ELRaffiei, "Satellite Swarm Survey and New Conceptual Design for Earth Observation Applications," The Egyptian Journal of Remote Sensing and Space Sciences, vol. 194, No. 1, February 2021.
2. Wubben, J. and F. Fabra, C.T Calafate, J. Cano, P. Manzoni, "A Novel Resilient and Reconfigurable Swarm Management Scheme," Computer Networks, vol. 194, April 2021.
3. Chen, M. and H. Wang, C. Chang, X. Wei, "SIDR: A Swarm Intelligence-Based Damage-Resilient Mechanism for UAV Swarm Networks," IEEE Access, vol. 8, April 2020.
4. Wagner, K.M. and J.T. Black, "Genetic-Algorithm-Based Design for Rideshare and Heterogeneous Constellations," Journal of Spacecraft and Rockets, vol. 57, No. 5, October 2020.
5. Azza, F. and P. De Marchi, M. Stoisa, P.G. Madonia, "Low-Thrust Reconfiguration Strategy for Flexible Satellite Constellations," Proceedings of the 2022 Small Satellite Conference, Logan, UT, August 2022.
6. Izzo, D. and L. Pettazzi, "Autonomous and Distributed Motion Planning for Satellite Swarm," Journal of Guidance, Control, and Dynamics, vol. 30, No. 2, April 2007.
7. Chen, Q. and C. Wei, "Satellite Swarm Reconfiguration Planning Based on Surrogate Models," Journal of Guidance, Control, and Dynamics, vol. 43, No. 9, July 2020.
8. Plice, L. and A.D. Perez, S. West, "HelioSwarm: Swarm Mission Design in High Altitude Orbit for Heliophysics," Proceedings of the 2019 AAS/AIAA Astrodynamics Specialist Conference, Portland, ME, August 2019.
9. Levinson-Muth, P. and L. Plice, J. Alvarellos, "HelioSwarm: Relative Orbit Maintenance Eccentric P/2 Lunar Resonant Orbit," Proceedings of the 2021 AAS/AIAA Astrodynamics Specialist Conference, Big Sky, MT, August 2021.
10. Levinson-Muth, P. and S. West, L. Plice, "HelioSwarm: Swarm Design Methods in Eccentric P/2 Lunar Resonant Orbit," Proceedings of the 2022 AAS/AIAA Astrodynamics Specialist Conference, Charlotte, NC, August 2022.
11. Randles, M. and D. Lamb, E. Odat, A. Taleb-Bendiab, "Distributed Redundancy and Robustness in Complex Systems," Journal of Computer and System Sciences, vol. 77, September 2009.
12. Uday, P. and K. Marais, "Designing Resilient Systems-of-Systems: A Survey of Metrics, Methods, and Challenges," Systems Engineering, vol. 18, November 2015.

13. Levinson-Muth, P. and L. Plice, "HelioSwarm: Swarm Establishment and Reconfiguration in Perturbed Eccentric Orbit", Proceedings of the 2023 AAS/AIAA Astrodynamics Specialist Conference, Big Sky, MT, August 2023 (in work).
14. Johnson, S.B. and J.C. Day, "Conceptual Framework for a Fault Management Design Methodology", Proceedings of the 2010 AIAA Infotech@Aerospace, Atlanta, GA, April 2010.