Concept of Operations for SWARM-EX: a Three CubeSat Formation-Flying Mission

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Abstract— **The Space Weather Atmospheric Reconfigurable Multiscale Experiment (SWARM-EX) is a distributed aeronomy instrument consisting of three 3U CubeSats operating in low Earth orbit. Supported by the National Science Foundation and NASA's CubeSat Launch Initiative, SWARM-EX aims to accomplish a challenging set of scientific and engineering objectives. The mission's scientific goals are focused on addressing outstanding aeronomy questions by making in-situ measurements of the equatorial thermospheric anomaly and equatorial ionospheric anomaly using Flux-Probe-Experiment and Planar Langmuir Probe sensors onboard each spacecraft. Engineering objectives are focused on advancing the state of the art in CubeSat swarming through a series of demonstrations and experiments. This paper presents three innovations that will enable SWARM-EX to overcome its significant challenges. First, the scientific objectives are formalized as a set of Primary Science Questions and Secondary Measurement Demonstrations, which are then translated into the spatial and temporal scales over which in-situ measurements must be made. These scales are then used to define the relative orbit geometries which the spacecraft must achieve. Second, a guidance, navigation, and control system is introduced which is able to acquire and maintain the required relative orbit configurations. The proposed system requires minimal input from controllers on the ground, provides passive safety at close inter-spacecraft separations, and is able to efficiently achieve large swarm reconfigurations with minimal propellant consumption by utilizing a novel hybrid propulsive/differential-drag control methodology. Third, a concept of operations is presented which enables the time- and propellant-efficient achievement of the mission's objectives while providing significant tolerance to on-orbit anomalies. The concept of operations is discussed in detail, including (1) the specific mission objectives to be addressed at each phase, (2) the control methodologies to be used at each phase and during transitions between phases, and (3) Δv budgets by phase and explanations for how they were obtained. The trades governing the control methodologies used are presented, along with some specific challenges faced in managing operations for the swarm as it varies from hundreds of meters' separation between spacecraft to thousands of kilometers'.**

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1. INTRODUCTION

Distributed space systems (DSS), a category that includes spacecraft formations, swarms, and constellations, offer significant advantages compared to traditional, monolithic spacecraft. Among these advantages are the possibility of distributing payload tasks across multiple spacecraft, potentially yielding greater robustness to failure, and the ability to realize a wide range of relative geometries between individual spacecraft. For the Space Weather Atmospheric Reconfigurable Multiscale Experiment (SWARM-EX), the acquisition, maintenance, and reconfiguration of the relative orbits between partner spacecraft is essential to the accomplishment of the mission's objectives. SWARM-EX is an upcoming formation-flying mission comprising three 3U CubeSats operating in low Earth orbit (LEO) as a distributed aeronomy sensor. Supported by the National Science Foundation and NASA's CubeSat Launch Initiative, SWARM-EX is currently under development by a multi-university partnership consisting of the University of Colorado Boulder, Stanford University, Olin College of Engineering, Georgia Tech, the University of South Alabama, and Western Michigan University [1].

The state of the art for in-situ aeronomy is illustrated by the Challenging Minisatellite Payload (CHAMP) and GRACE missions. Data obtained from the onboard accelerometers and planar Langmuir probe (PLP) of the CHAMP spacecraft has been used extensively in research of the upper atmosphere, including investigations of the the equatorial ionization anomaly (EIA) and the equatorial thermosphere anomaly (ETA), [2] and neutral density [3]. CHAMP consisted of a single spacecraft, however, and was consequently limited in its ability to revisit specific regions of the ionosphere/thermosphere at timescales less than one orbit period. Similarly, accelerometer data from the two GRACE spacecraft has been used to better characterize neutral density changes in the thermosphere in response to solar and geomagnetic activity [4]. A new generation of miniaturized DSS is poised to push the boundaries of what is achievable in optical navigation [5], heliophysics [6], asteroid mapping [7], and X-ray astronomy [8], among other fields. Joining these, SWARM-EX represents an exciting opportunity to simultaneously advance the state of the art in both spacecraft formation-flying and in-situ aeronomy by combining a distributed architecture and advanced relative guidance, navigation, and control (GNC) methodologies with sophisticated scientific instruments.

The SWARM-EX mission has an ambitious set of scientific and engineering objectives intended to address outstanding questions in aeronomy and advance the state of the art in CubeSat swarming. The scientific objectives are focused on investigating two phenomena occurring in the equatorial ionosphere-thermosphere (I-T) region: the EIA and the ETA. By making in-situ measurements of neutral and plasma densities at various spatial and temporal scales, SWARM-EX will improve the current understanding of the formation and evolution of the EIA/ETA, with implications for space weather modeling and satellite communications. The mission's engineering objectives will advance the state of the art in CubeSat swarming by demonstrating several important capabilities for CubeSat swarms, including passively safe, autonomous formation acquisition and maintenance by more than two spacecraft, and a novel hybrid propulsive/differential-drag control methodology [9].

The accomplishment of the SWARM-EX mission's challenging objectives necessitates the imposition of a rigorous and detailed set of requirements for every aspect of the mission and spacecraft design. For SWARM-EX, the top-level mission requirements are formalized as Primary Science Questions (PSQs) and Secondary Measurement Demonstrations (SMDs). The PSQs concisely define those outstanding questions in aeronomy which the SWARM-EX mission specifically seeks to address, and are used to derive detailed scientific and measurement objectives which can more readily be translated into requirements for other spacecraft subsystems. The SMDs define a set of specific in-situ measurements which would contribute to an improved characterization of the I-T region. These measurements are in addition to those derived from the PSQs, and serve as an opportunistic way to increase the total scientific output of the SWARM-EX mission. Taken together, the PSQs and SMDs dictate the key aspects of the mission and spacecraft design, including its distributed architecture and the high level of capability of the individual spacecraft.

A crucial step for any space mission is the development of a concept of operations (ConOps). A ConOps must achieve the marriage between the mission's objectives and the capabilities and limitations of its spacecraft in a manner that is robust and efficient. This paper presents the ConOps for SWARM-EX, beginning with a detailed discussion of the mission's scientific objectives in Section 2, including a description of the scientific instruments onboard each spacecraft and their capabilities. Next, Section 3 provides an overview of the spacecraft design, including key hardware components and their layouts within the spacecraft structure. The mission's specific relative orbit configurations, and GNC system which will enable their realization, are described in Section 4. Section 5 presents the ConOps itself, including detailed discussions of each mission phase, as well as the transitions between phases. Finally, Section 6 offers concluding remarks and the way forward for the SWARM-EX mission.

2. Scientific Objectives

In this section, additional background information regarding the mission's scientific objectives is provided, followed by a detailed discussion of those objectives and their formalization as PSQs and SMDs. The scientific instruments and their function are also discussed.

Background

The I-T region, specifically between 350-550 km altitude, is a highly dynamic region of the upper atmosphere which is sensitive to solar activity and geophysical variability that is not easily quantifiable. There are mechanisms in the I-T region that are not fully understood despite numerous initiatives to better characterize this region and thereby forecast the effects of solar activity on the near-Earth space environment. One of the largest limitations in understanding the I-T region is the lack of simultaneous measurements of various I-T properties. Most of the observational data and knowledge of the I-T region comes from single-satellite missions launched in the 1960s, '70s, and '80s, taking measurements in a target region once per orbit. With plasma and neutral parameters responding to perturbations at different timescales, often less than the orbital period of the observing spacecraft, data sets from these early missions suffer from significant spatial-temporal ambiguity. Overcoming this limitation and better characterizing the near-Earth space environment has significant implications for atmospheric drag modeling and orbit determination, and space/ground-based operations.

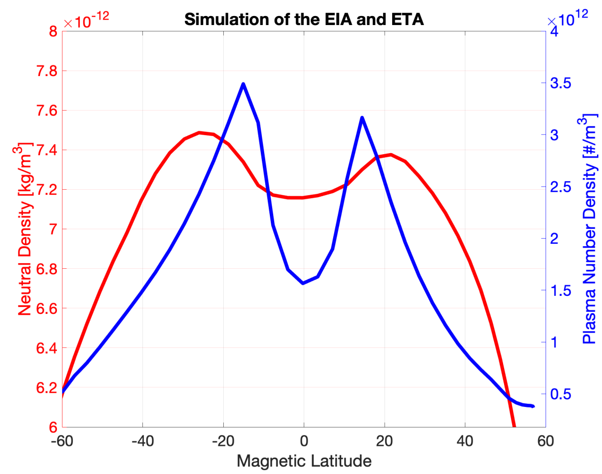

Figure 1. Satellite fly-through scheme simulating instrument sampling of the EIA and ETA using the high-resolution TIEGCM.

To confine the I-T to a more manageable observational region, two specific features of the low-latitude I-T region are discussed. The first is the EIA, also known as the Appleton Anomaly, a feature of the low-latitude ionosphere [10]. This feature is a result of an upward vertical drift associated with the eastward electric fields produced by the ionospheric E-region dynamo, called the fountain effect [11]. The EIA is recognizable as a double-peak shape with crests at $\pm 15°$ in magnetic latitude and a trough at the magnetic equator, shown in blue in Figure 1. Note that the data in this figure uses the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM) to simulate the coupled thermosphere-ionosphere system. The second feature is the ETA, occurring in the low-latitude thermosphere. The ETA is also recognizable as a double-peak shape, with crests at $\pm 20° - 30°$ in magnetic latitude and a trough at the magnetic equator, shown in red in Figure 1. The similarities and differences between these two features have been investigated using electron and neutral density measurements taken by the CHAMP mission [2]. While the EIA and its formation mechanisms have been well understood for decades, there is not yet a full understanding of the ETA's structure, formation, and evolution processes, as well as the extent of its coupling with the EIA.

Objectives

SWARM-EX is designed to address outstanding aeronomy questions relating to the formation and evolution of the EIA and ETA using 3 identical formation-flying spacecraft to make in-situ measurements of the I-T region. The target region to capture the EIA and ETA is between 350-550 km in altitude, between $\pm 50°$ in geographic latitude, and during local times of 08:00-20:00. The motivation is to advance the understanding of spatial and temporal gradients in the EIA and ETA to improve the understanding of the underlying physics of I-T disturbances. This goal has been discretized into PSQs and SMDs, which are listed in Tables 1 and 2, respectively.

Table 1. Primary Science Questions

Designator	Description
PSQ-1	How persistent and correlated are the plasma density and neutral oxygen in the EIA and ETA features?
PSQ-2	Over what timescales, less than 90 minutes, can changes be observed in EIA and ETA properties due to non-migrating tides and geomagnetic activity?

Unlike previous efforts relying on a single spacecraft, SWARM-EX can cross-correlate measurements of the EIA and ETA on suborbital timescales, which allows spatial and temporal changes to be differentiated. If the two features are deemed persistent during a given period, then those measurements will address the higher level science goals associated with PSQ-1. This science question focuses on characterizing the spatial variations associated with the EIA and ETA during varying local times, longitudes, and geomagnetic conditions. If the features violate the persistence criteria, then the measurements collected will address the higher level science goals associated with PSQ-2, which aim to characterize temporal gradients to observe how traveling disturbances and fast-moving perturbations influence the features.

Table 2. Secondary Measurement Demonstrations

Designator	Description
SMD-1	Cross-calibrate plasma and atomic oxygen (AO) measurements from each spacecraft by making measurements located within 100 km of each other
SMD-2	Demonstrate horizontal plasma gradient density measurements at scales of $\leq$10 km
SMD-3	Estimate mass density by observing the relative motion of two spacecraft when they are separated by $<$100 km
SMD-4	Estimate density gradients at vertical scales $\leq$10 km

The SMDs are intended to leverage the distributed architecture of SWARM-EX to supplement the PSQs and gain more insight on the I-T observations. SMD-1 aims to cross-calibrate the scientific instruments when they are close together in order to characterize any biases in the instruments. The goal of SMD-2 is to capture small-scale, fast-moving plasma perturbations in the ionosphere. SMD-3 is an effort to recover neutral density based on observations of the change in the spacecraft relative orbits due to atmospheric drag and measurements from the scientific payload. This measurement demonstration is tightly linked with the SWARM-EX GNC system, and will be addressed in greater detail in a subsequent section. Finally, SMD-4 will attempt to estimate the neutral temperature by extracting the scale height coming from vertical gradients in the neutral density.

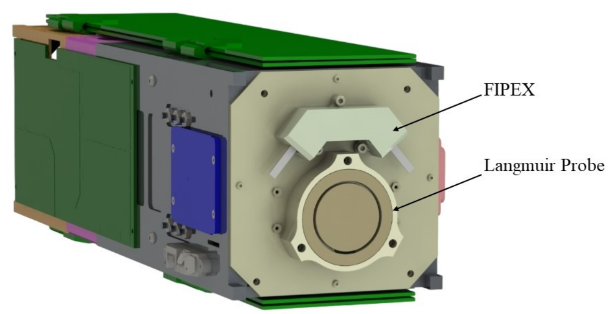

Figure 2. Instrument placement within spacecraft structure.

Instruments

Onboard each SWARM-EX spacecraft are two scientific instruments situated together on one 10 cm x 10 cm face that will take in-situ measurements of the EIA and ETA: a PLP to measure the ion density, and an atomic oxygen-sensing instrument called Φ-Probe EXperiment (FIPEX) to capture the neutral density [12]. These instruments are shown in Figure 2. Orion Space Solutions is providing their Ionospheric Sensing (I-SENSE) electronic boards, which have been flown in past satellite missions, to process ion density signals coming from the PLP. The I-SENSE boards are calibrated to capture the range of ion densities SWARM-EX will expect during science operations.

While the I-SENSE boards and PLP have a strong flight heritage, FIPEX is a novel instrument that has not yet been successfully flown in the space environment. The FIPEX sensors on SWARM-EX are developed and tested by the Institute of Space Systems at the University of Stuttgart. The FIPEX sensors are small solid electrolyte sensors that can measure atomic oxygen number densities along a wide pressure range and have been flown on several sounding rocket campaigns. Since the FIPEX sensors are small and novel, SWARM-EX will have two FIPEX sensors on each spacecraft to observe the effects of the space environment on the sensors' performances and reduce the risk of instrument failure.

3. Spacecraft Design

In addition to the scientific instruments discussed in the previous section, each identical SWARM-EX spacecraft pos-

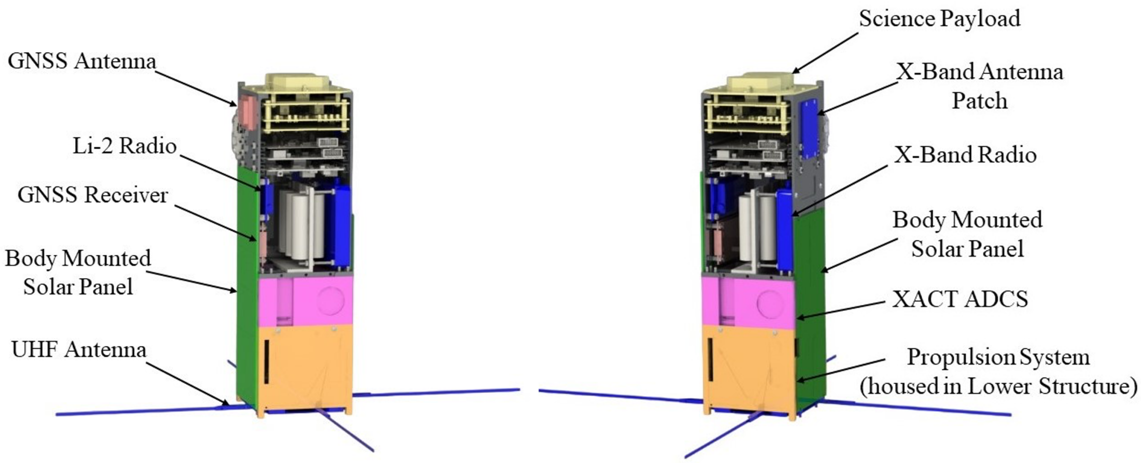

Figure 3. **Spacecraft hardware components.**

sesses the requisite hardware components that enable them to operate safely and effectively as members of a swarm. Rather than an exhaustive description of the spacecraft structural design, only those critical hardware components which have implications for the development of the ConOps is discussed in this section. These critical hardware components are: (1) the GNSS receiver and antenna, (2) X-band and UHF radio transceivers and antennas, (3) the attitude determination and control system (ADCS), (4) the two-phase cold gas propulsion system, and (5) dual-deploy solar panels.

Wherever possible, SWARM-EX utilizes commercial off-the-shelf (COTS) hardware components. This includes the GNSS receiver, which is an OEM719 multi-frequency GNSS receiver provided by Novatel [13]. This receiver and its associated antenna are shown in red in Figure 3. The ability of the spacecraft to communicate, both with operators on the ground and autonomously among members of the swarm, is crucial to the success of the SWARM-EX mission. Each spacecraft is equipped with a deployable, omnidirectional ultra-high frequency (UHF) antenna system provided by ISISpace [14], which feeds into an AstroDev Lithium-2 radio. Additionally, each spacecraft possesses a Bluefin X-Band radio and antenna provided by Blue Cubed. Shown in Figure 3 in blue, these communication systems enable downlink and uplink of telemetry and telecommands, in addition to serving as an intersatellite link (ISL) which permits communication between swarm members.

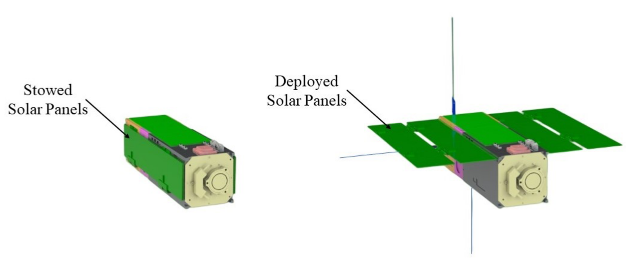

Figure 4. **Spacecraft with solar panels and UHF antenna deployed (left) and stowed (right).**

An XACT-15 ADCS provided by Blue Canyon Technologies [15] enables three-axis attitude control of SWARM-EX spacecraft, which must balance a complex set of competing attitude requirements [16]. This system is shown in purple in Figure 3. A high volumetric efficiency, 3D printed cold gas propulsion system is provided by Georgia Tech. The propulsion system is shown within the lower structure in Figure 3, highlighted in orange. This system includes a main propellant tank, plenum, and nozzle. R-236fa propellant is stored as a two-phase liquid-vapor mixture to further increase volumetric efficiency. In combination with the ADCS, the propulsion system enables SWARM-EX spacecraft to perform maneuvers in any direction desired. Each SWARM-EX spacecraft has both body-mounted and dual-deploy solar panels. These are shown in Figure 3 in green. Following launch and deployment, the dual-deploy panels utilize a burn resistor to cause a piece of fishing line holding them in their stowed position to fail, allowing them to fully open. The stowed and deployed configurations of the dual-deploy solar panels and UHF antenna are shown in Figure 4. Note that the use of dual-deploy solar panels enables a theoretical minimum spacecraft cross-sectional area of 100 cm^2 and a maximum cross-sectional area of 1409 cm^2. This is relevant to the use of drag-based control and will be discussed in the subsequent section.

4. Guidance, Navigation, and Control

The level of capability of the SWARM-EX spacecraft motivates the development of a GNC system which is able to fully utilize this capacity while enabling safe, propellant-efficient accomplishment of the mission objectives. In this section, the specific parameterizations of the absolute and relative orbits are introduced. Next, the requirements imposed on the absolute and relative orbits are discussed. An overview of the onboard GNC system developed for SWARM-EX is presented, along with a detailed discussion of SMD-3, which is related to the navigation filter design.

Orbit Parameterization

Absolute orbits for the SWARM-EX mission are parameterized in terms of quasi-nonsingular (QNS) orbital elements, defined as

$$\boldsymbol{\alpha} = \begin{bmatrix} a \\ u \\ e_x \\ e_y \\ i \\ \Omega \end{bmatrix} = \begin{bmatrix} a \\ \omega + M \\ e\cos\omega \\ e\sin\omega \\ i \\ \Omega \end{bmatrix} \tag{1}$$

The QNS orbital elements modify the classical Keplerian orbital elements to instead use the eccentricity vector, defined as

$$\boldsymbol{e} = \begin{bmatrix} e_x \\ e_y \end{bmatrix} \tag{2}$$

and the mean argument of latitude, u. This modification avoids the potential for singularities in the classical Keplerian orbital elements in the case of near-circular orbits.

Relative orbital elements (ROE) are used to parameterize the relative orbits. The ROE are defined in terms of the absolute QNS orbital elements for a chief, denoted by the subscript c, and a deputy, denoted by the subscript d, as

$$\delta\boldsymbol{\alpha} = \begin{bmatrix} \delta a \\ \delta\lambda \\ \delta e_x \\ \delta e_y \\ \delta i_x \\ \delta i_y \end{bmatrix} = \begin{bmatrix} (a_d - a_c)/a_c \\ (u_d - u_c) + (\Omega_d - \Omega_c)\cos(i_c) \\ e_{x_d} - e_{x_c} \\ e_{y_d} - e_{y_c} \\ i_d - i_c \\ (\Omega_d - \Omega_c)\sin(i_c) \end{bmatrix} \tag{3}$$

where the relative eccentricity vector, $\boldsymbol{\delta e}$, and relative inclination vector, $\boldsymbol{\delta i}$, are defined as

$$\boldsymbol{\delta e} = \begin{bmatrix} \delta e_x \\ \delta e_y \end{bmatrix} \tag{4}$$

$$\boldsymbol{\delta i} = \begin{bmatrix} \delta i_x \\ \delta i_y \end{bmatrix} \tag{5}$$

This parameterization of the relative orbit has several advantages, including the straightforward interpretation of relative orbit geometry and the accurate, analytical inclusion of perturbations and maneuvers [17].

This convenient geometric interpretation is shown in Figure 5, which maps the ROE into the curvilinear radial-tangential-normal (RTN) frame centered on the chief spacecraft [18]. This curvilinear reference frame is similar to the traditional, Cartesian RTN frame, also known as the local-vertical local-horizontal frame. However, to retain validity at the large inter-spacecraft separations experienced by the SWARM-EX mission, the tangential and normal directions are defined in terms of the arc length along and perpendicular to the reference orbit. To denote these curvilinear axes, $\hat{o}_\theta$ is used to represent the direction along the reference orbit, and $\hat{o}_\phi$ is used to represent the direction perpendicular to the reference orbit. The radial direction, denoted $\hat{o}_r$, is not treated as curvilinear and refers to the direction along the chief absolute position vector. For near-circular orbits, relative motion in the RT plane, shown at the top of Figure 5, is described by an ellipse with semi-major axis $2a\delta e$ and semi-minor axis $a\delta e$, where δe is the magnitude of the relative eccentricity vector. The center of this ellipse is offset in the tangential direction by $a\delta\lambda$, the mean along-track separation between chief and deputy spacecraft. Relative motion in the RN plane, shown at the bottom of Figure 5, is described by an harmonic oscillation where the maximum separations in the radial and normal directions are determined by the magnitudes of the relative eccentricity and inclination vectors, respectively.

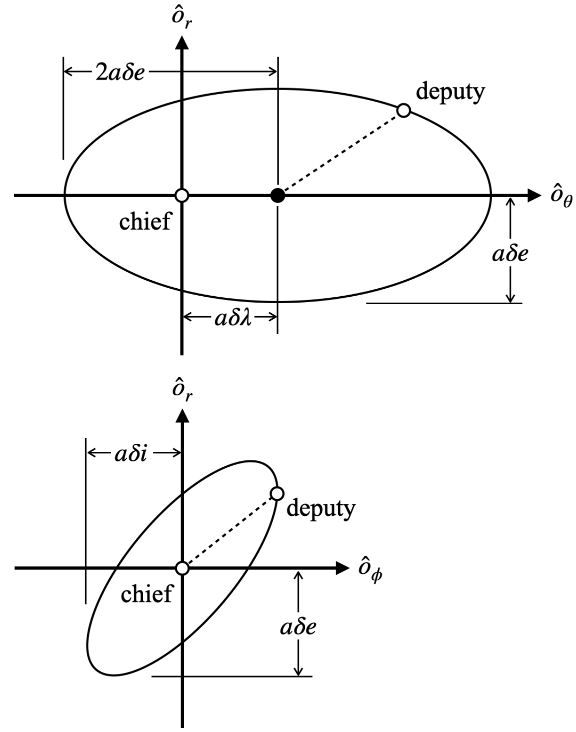

Figure 5. Geometric interpretation of ROE in curvilinear RTN reference frame.

Orbit Requirements

The absolute orbit requirements for the SWARM-EX mission derive from the need to maximize the amount of time that the spacecraft spend in the region of interest. From this emerge requirements on the altitude and inclination of the absolute orbits. The required relative orbits for SWARM-EX are more complicated, with several, often conflicting configurations needed in order to satisfy all mission objectives.

Table 3. Orbit Requirements Summary

Source	Requirement
PSQ-1.D	6798 km $\leq a \leq$ 6853 km
PSQ-1.D	1200 km $\leq \lvert a\delta\lambda\rvert \leq$ 1400 km, $a\delta e \leq$ 15 km
PSQ-1.E	$\lvert i\rvert \geq 50°$
SMD-2	$\lvert a\delta\lambda\rvert \leq$ 10 km
SMD-3	$\lvert a\delta\lambda\rvert \leq$ 100 km, $a\delta e \leq$ 10 km
SMD-4	$\lvert a\delta\lambda\rvert \leq$ 10 km, $a\delta e \geq$ 10 km

The requirements on the absolute and relative orbits are summarized in Table 3. Note that this is not an exhaustive list and only the most restrictive requirements are shown in cases where there is overlap. For simplicity, this set of requirements is refined into three distinct nominal relative orbit configurations. The first of these relative orbit configurations requires that the deputies maintain a mean along-track separation less than or equal to 10 km with respect to the chief, with the maximum radial separation also less than 10 km. The second configuration requires that the deputies

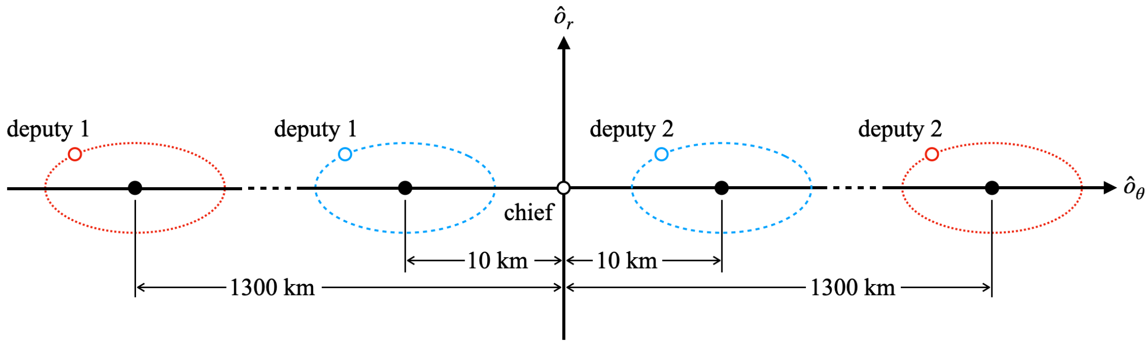

Figure 6. Nominal curvilinear RT plane relative orbits at small (blue dashed) and large (red dotted) inter-spacecraft separations; figure not to scale.

have a large along-track separation, between 1200 and 1400 km, while maintaining a maximum radial separation less than 15 km. Note that this along-track separation is between each spacecraft, meaning the total dispersion of the swarm in this configuration is between 2400 and 2800 km. The motion in the RT plane of these first two relative orbit configurations is shown in Figure 6.

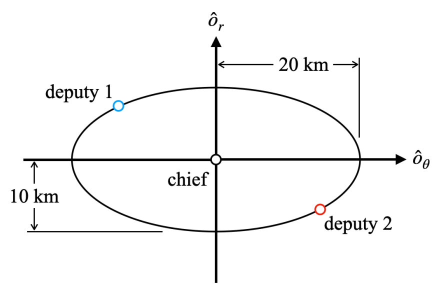

Figure 7. Nominal curvilinear RT plane relative orbit with large, periodic radial separation.

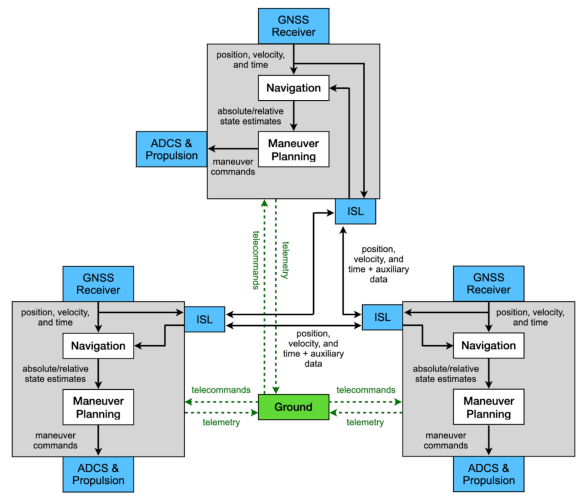

Figure 8. Diagram of SWAG and interfaces.

The third relative orbit configuration requires less than 10 km mean along-track separation with a maximum radial separation greater than 10 km. To satisfy these requirements, a relative orbit is selected which has the deputies co-orbiting the chief spacecraft, with zero mean along-track separation, as distinct from the first two configurations which each have the swarm dispersed in the along-track sense. The motion in the RT plane of this relative orbit configuration is shown in Figure 7. Note that the relative eccentricity and inclination vectors are phased to ensure that the two deputies remain on opposite sides of their shared relative orbit.

Guidance, Navigation, and Control Subsystem

The autonomous acquisition and maintenance of these relative orbit configurations necessitates the inclusion of a GNC system which is able to accurately estimate the spacecraft absolute and relative orbits, as well as plan and execute maneuvers. The SWARM-EX Autonomous Guidance, Navigation, and Control (SWAG) system provides this capability. Each CubeSat hosts an identical implementation of SWAG, with the designation of roles as chief or deputy provided from the ground via telecommand. SWAG consists of two modules: navigation and control. Guidance is provided via telecommand in the form of sets of nominal ROE to be acquired and maintained by the deputies. A graphical depiction of this system and its interfaces with other key spacecraft components is shown in Figure 8.

The SWAG navigation module of each spacecraft estimates its host spacecraft's absolute orbit, in addition to its relative orbit with respect to the other swarm members. GPS PVT solutions for all swarm members are provided as measurements. Local measurements come from the onboard GPS receiver, while remote measurements are received from the partner spacecraft via the ISL. SWAG must provide consistent performance across a wide range of inter-spacecraft separations. Therefore, state estimation is performed in an unscented Kalman filter (UKF), which is able to appropriately handle the nonlinear dynamics associated with large inter-spacecraft separation distances. The absolute and relative state orbit estimates are then provided to the control module.

To ensure passive safety, the SWAG control module utilizes the well-known method of e-/i-vector separation [19]. This methodology provides a safe separation between spacecraft in the plane perpendicular to the flight direction, is robust to orbit perturbations, and results in predictable control cycle that aids in verification and eases ground operations. Control actions for SWARM-EX have three possible forms. The first utilizes the cold gas propulsion system to perform triplets of maneuvers in order to control those ROE which define the in-plane relative motion: δa, $\delta\lambda$, and $\boldsymbol{\delta e}$ [20]. Single impulses are used to control the out-of-plane relative motion, which is described by $\boldsymbol{\delta i}$. The second is a drag-based approach, which uses attitude control to modulate the spacecraft cross-sectional areas with respect to the flight direction. As shown in Figure 4, the minimum cross-sectional area would be achieved by having one 10 cm x 10 cm face in the flight direction, while the maximum cross-sectional area occurs when the plane formed by the dual-deploy solar panels is perpendicular to the flight direction. In this way, a relative ballistic coefficient between spacecraft is introduced, which is used to control the in-plane components of the relative orbit. Note that, while the large difference in cross-sectional area allows the relative ballistic coefficient between spacecraft to be varied by up to 1309%, other constraints on the spacecraft attitudes make this practically unachievable. However, significant control authority is still available through this methodology, and relative ballistic coefficients up to 600% can be sustained. Finally, a hybrid method which combines propulsive and drag-based control is used [9]. This last method is attractive for several reasons. It affords SWARM-EX the possibility of performing formation maintenance without expending propellant. Additionally, it offers the SWARM-EX team a trade between the timeliness of large along-track reconfigurations and the amount of propellant consumed in the reconfiguration, giving ground operators greater flexibility.

Relative Accelerometry

Atmospheric drag is typically the largest source of orbit determination uncertainty for spacecraft in LEO [21]. Consequently, the estimation of atmospheric density remains an area of active research. The SWARM-EX mission's distributed architecture presents a unique opportunity to advance the state of the art in this field by using the entire swarm as a distributed relative accelerometry sensor, which is formalized as SMD-3. The acceleration vector due to atmospheric drag can be expressed as

$$\boldsymbol{a}_{\text{drag}} = -\frac{1}{2}\rho B v_{\text{rel}}^2 \frac{\boldsymbol{v}_{\text{rel}}}{\|\boldsymbol{v}_{\text{rel}}\|_2} \tag{6}$$

where ρ is the atmospheric density, the ballistic coefficient, B, is defined in terms of the coefficient of drag, c_D, spacecraft cross-sectional area, A, and mass, m, as

$$B = \frac{c_D A}{m} \tag{7}$$

and $\boldsymbol{v}_{\text{rel}}$ is the spacecraft's velocity vector relative to the atmosphere. By varying the ballistic coefficient of the chief and deputies through attitude control, a relative ballistic coefficient is introduced, which can be expressed as

$$\Delta B = B_d - B_c \tag{8}$$

By assuming that the orbit is circular and that the motion of the atmosphere relative to the orbiting spacecraft is negligible, the time rate of change of the relative semi-major axis, δa, can be expressed in terms of this relative ballistic coefficient as

$$\frac{d(\delta a)}{dt} = \rho \Delta B n a \tag{9}$$

where n is the mean motion. This simplified model illustrates how information about the drag environment can be extracted through observation of the evolution of the relative orbits over time.

SWARM-EX approaches this problem from two directions. The first approach is through SWAG, which will perform simultaneous navigation and characterization (SNAC) of the drag environment by augmenting its navigation filter state with additional parameters related to atmospheric drag [22]. These additional parameters include the time rates of the absolute and relative semi-major axes, and the absolute and relative ballistic coefficients. By estimating these parameters within the navigation filter alongside the absolute and relative orbits, this SNAC approach aims to leverage the cross-covariance relationship between state parameters in order to improve the orbit determination accuracy, while gaining valuable information about the drag environment that can be used to aid in drag-based and hybrid control. The second approach to the problem of recovering neutral density is through ex post facto precise relative orbit determination. By coupling error-canceling combinations of raw GPS pseudorange and carrier-phase measurements downlinked by the SWARM-EX spacecraft with integer ambiguity resolution techniques, relative navigation accuracy better than one centimeter (3D RMS) is achievable [23][24]. Additionally, this ex post facto approach can also leverage AO measurements obtained from the FIPEX sensors as a proxy for direct measurement of atmospheric density, since AO is the dominant species in the operational altitudes for SWARM-EX. With these powerful techniques, the characterization of the drag environment may be accomplished with greater accuracy than is possible with a single spacecraft.

5. Concept of Operations

In this section, a brief overview of the SWARM-EX mission timeline is provided, followed by an explanation of the use of a novel reduced-order model to derive quantitative estimates for Δv consumption and minimum inter-spacecraft separation distances over the mission lifetime. Next, each phase of the SWARM-EX mission is discussed in detail, including the specific mission objectives to be addressed at each phase and during transitions between phases. From the perspective of mission design, the primary objectives of the SWARM-EX mission are to (1) better characterize the spatial and temporal variability of the EIA and the ETA and (2) demonstrate cutting-edge engineering technology through autonomous formation-flying control algorithms. Flying in formation, the SWARM-EX CubeSats will be coordinated to address these aims by alternating between conducting Science (SCI) experiments and GNC experiments, where the former are generally characterized by much larger mean along-track separations between the spacecraft than the latter. During SCI experiments, the three SWARM-EX spacecraft will separate from one another using a combination of onboard propulsion (PROP) and differential drag (DD) to make in-situ measurements profitable to a better understanding of the EIA and ETA. The spacecraft are then brought much closer together during GNC experiments, where they will further demonstrate fuel balancing through the aforementioned hybrid propulsive/differential-drag control scheme and autonomous relative orbit determination and prediction. A mean along-track separation of $\approx$10 km nominally partitions these two experiments.

The SWARM-EX ConOps is divided into the following categories: Deployment, Systems Commissioning, GNC Experiments, and Science Experiments. More broadly, the

SWARM-EX mission can be segmented into the **Primary Mission** (≈157 days), which covers Deployment, Systems Commissioning, GNC Experiments 1-4, and Science Experiments 1-9, and the **Extended Mission** (≈110 days), which covers Science Experiments 10-18 and GNC Experiments 5-6. Figure 9 provides a visualization of the ConOps timeline for SWARM-EX and highlights the order of experiments discussed below.

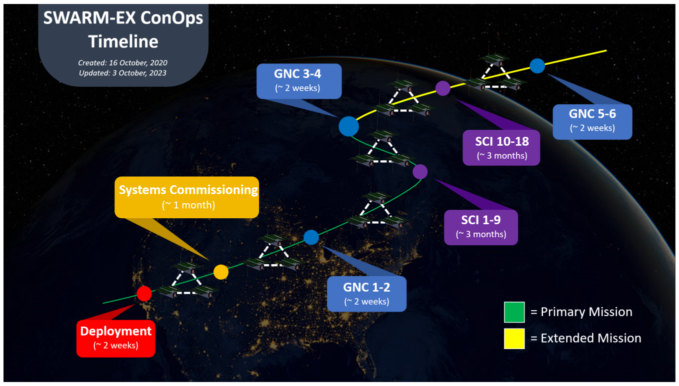

Figure 9. A visualization of the ConOps for SWARM-EX detailing the various mission phases.

The cycling of these experiments engenders complex challenges for the SWARM-EX team, particularly with regards to managing propellant consumption, and ensuring all spacecraft remain power-positive during the Primary Mission phases. Enabling effective SCI and GNC experiments has required the SWARM-EX team to thoroughly plan out the operations of SWARM-EX and craft the on-orbit sequence of events delineated below. This process was aided by the use of a reduced-order model for the design of formation-flying missions.

Reduced-Order Model

The already significant challenge of anticipating propellant consumption for a spacecraft is compounded for DSS, which must also consider the maintenance and reconfiguration of passively safe relative orbits between partner spacecraft. To overcome this challenge, a reduced-order model was developed to aid in the mission design for spacecraft swarms [25]. This model provides accurate information for mission designers regarding propellant consumption for formation maintenance and reconfiguration, safety, and the timeliness of maneuvers and reconfigurations.

The reduced-order model takes as inputs the nominal absolute and relative orbits and the formation control window sizes, which define the allowed deviation from the nominal relative configuration. For reconfigurations between different nominal relative orbits, the method, either propulsion or differential drag, and the allowed time duration of the reconfiguration are also provided as inputs. Outputs include, but are not limited to, the minimum separation between spacecraft in the RN plane over the given time duration, the Δv cost of maintaining the specified relative configuration, as well as the cost to reconfigure from the previous relative configuration. An example of the use of this reduced order model is shown in Table 4 for two segments of the SWARM-EX mission. The model was used throughout the development process for the ConOps, and is the source of subsequent Δv budgeting information.

Table 4. **Reduced-order model example inputs and outputs.**

Time [days]	2	7
Tasks	SCI	GNC-1
Inputs		
Mean Along-track Distance [km]	20.000	10.000
Max Radial Distance [km]	1.000	1.000
Max Cross-track Distance [km]	1.000	1.000
$a\delta\lambda$ Control Window [km]	1.000	1.000
$a\delta e$ Control Window [km]	0.100	0.100
$a\delta i$ Control Window [km]	0.100	0.100
Outputs		
Min RN Plane Separation [km]	0.649	0.649
Formation-keeping Δv [cm/s]	0.258	0.258
Reconfiguration Δv [cm/s]	0.079	0.000
Total Δv [cm/s]	0.337	0.258

Primary Mission

The mission designers of SWARM-EX developed the operations plan for the Primary Mission by imposing a development paradigm centered about three principles:

1. Fulfillment of key scientific and engineering objectives
2. Knowledge of spacecraft mean along-track separation distances and methods used to alter/maintain the relative orbits
3. Scheduling the operational states of critical communication and scientific hardware

While principle (1) is self-evident for any satellite mission, the formation flying component of SWARM-EX necessitates the coupling of principles (2) and (3), especially given the difference in nature between the scientific and engineering aims of the mission. Whereas SCI experiments require nominal mean along-track separations of $a\delta\lambda \in [10, 1475]$ km to evaluate the spatial structure and variability of the EIA/ETA, GNC experiments are characterized by the significantly smaller along-track separations of $a\delta\lambda \in [0, 10]$ km to demonstrate novel autonomous control capabilities while in close proximity. Consequently, satisfaction of SCI and GNC goals requires that mission designers plan for the spacecraft swarm to expand and contract at different points in the mission. In order to minimize the amount of propulsion expended, the operations plan must also be designed to utilize the appreciable orbital effects of atmospheric drag in LEO for maneuvers and formation keeping. Subsequently, the pointing constraints required for efficient DD expansion/contraction must be reconciled with the attitude constraints imposed by the SCI instrument suite, in addition to the careful balancing required to concurrently maintain a stable power cycle and regularly point the X-Band antenna towards the ground station at each pass [16]. In the context of this sophisticated problem, this development paradigm serves as the impetus for Figure 10, which details in full the ConOps for the Primary Mission according to the aforementioned criterion. Each phase of the mission is described more thoroughly in subsequent sections.

Deployment and Systems Commissioning—During the mission's Deployment phase, which is estimated to last $\approx$ 1

	Primary Mission																					
Time [days]	0	5	19	21	26	28	30	32	34	36	43	50	52	57	70	80	110	120	133	138	140	147
Length [days]		14	2	5	2	2	2	2	2	7	7	2	5	13	10	30	10	13	5	2	7	7
Phase	**Deployment**	**Systems Commissioning**								**GNC EXP**		**Science**									**GNC EXP**	
Tasks		UHF	SA	ADCS	X-Band	ISL	PROP	GNC	SCI	GNC-1	GNC-2	SCI-1	SCI-2	SCI-3	SCI-4	SCI-5	SCI-6	SCI-7	SCI-8	SCI-9	GNC-3	GNC-4
Pointing/Description		Tumbling		3-Axis Stable						Nominal GNC Operations		**Expansion 1**					**Contraction 1**				Optimal Hybrid (PROP/DD) Control	
Mean Separation [km]	1-20	20	20	20	20	20	20	20	20	10	10	10->250	250->300	300->800	800->1300	1300	1300->800	800->300	300->250	250->10	10	10
Formation Keeping		DD					PROP			PROP		N/A										
Formation Reconfiguration		N/A								PROP	PROP	DD			PROP	N/A	PROP	DD			PROP	PROP
UHF Uplink		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
UHF Downlink		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
X-Band Downlink					X				X	X	X	X	X	X	X	X	X	X	X	X	X	X
ENG-1: CDMA Downlink					X				X	X	X										[1]	
ENG-2: UHF Cross-Link						X	X	X	X	X	X	X	X						X	X	X	X
ENG-3: Propulsion							X	X		X	X				X		X				X	X
ENG-4: Formation Flying								X		X	X	X	X	X	X	X	X	X	X	X	X	X
ENG-5: Collision Avoidance								X		X	X	X								X	X	X
ENG-6: Expand & Reconnect												X	X	X	X		X	X	X	X		
FIPEX ON									X			X	X	X	X	X	X	X	X	X		
LP ON									X	X	X	X X	X	X	X	X	X	X	X	X X		
PSQ-1: Persistance															X	X	X					
PSQ-2: Timescales															X	X	X					
SMD-1: Cross Calibration										X											X	
SMD-2: Horiz. Small Scale										X	X										X	X
SMD-3: Relative Accel.												X								X		
SMD-4: Vertical Gradients																						
Total Delta-V Cost [cm/s]							0.074	0.074	0.074	0.337	0.258	0	0	0	0	0	0	0	0	0	0.258	0.258

Figure 10. A breakdown of the ConOps for the SWARM-EX Primary Mission.

week, SWARM-EX plans to launch in Q3 2024 from the International Space Station (ISS).[2] Launching from the ISS will nominally provide the SWARM-EX CubeSats with an inclination of 52° and an initial altitude of ≈420 km, which is desired to achieve sufficient mission lifetime above 400 km and sufficiently analyze the ionosphere-thermosphere region. Physical deployment will initiate a 45-minute timer onboard each spacecraft, where the termination of the timer results in initial spacecraft software boot into low-power mode.

The end of deployment defines the transition to Systems Commissioning, which will last ≈5 weeks. During this phase, onboard hardware will be tested for functionality in a progressive fashion (i.e., from minimal to full complexity). With each spacecraft of SWARM-EX hosting a UHF radio, establishing UHF communication to all three spacecraft will be the first priority of mission operators. To maintain control over this process and provide the exercise of ground station development, SWARM-EX will have UHF ground station locations at CU Boulder, Olin College, and Georgia Tech, where each university's operations team will nominally be given responsibility for one of the three spacecraft.[3] After both the uplink and downlink capabilities of each spacecraft have been thoroughly verified, mission operators will then command each spacecraft to initiate solar array (SA) deployment. The Electrical Power System will also be checked for nominal performance at this time; operators will use a combination of current/voltage and State of Charge readings to verify successful SA deployment. Once the swarm has the ability to generate sufficient power from the SAs, operators will then transition out of low-power mode and cease spacecraft tumbling by enabling the ADCS. ADCS validation will consist of operators cycling through the various expected attitude profiles of the mission, with the final profile being that which allows for the spacecraft to downlink using the X-Band radio.[4] Coordination with the outsourced X-Band ground station provider will also be settled at this time. Completion of ADCS commissioning will be met by UHF crosslink verification over the ISL between the spacecraft, a requirement of the onboard GNC algorithms so that each spacecraft has frequent knowledge of the orbital states of the other two. Mission operators will then move into commissioning the onboard propulsion units in tandem with the GNC software by verifying propulsive valve functionality and conducting minimal-risk formation keeping maneuvers. The conclusion of Systems Commissioning will be set by the SCI team working with ground operators to separately verify the outputs of each onboard FIPEX and Langmuir Probe sensor in preparation for the ensuing SCI experiments.

GNC-<1:2>: Nominal GNC Operations—Following Systems Commissioning, the SWARM-EX CubeSats will begin nominal operations by taking advantage of the initial close proximity to conduct the first two GNC experiments, denoted GNC-1 and GNC-2. GNC-1 will be an extension of the commissioning phase of the GNC system, whereby the onboard autonomous control algorithms will be directed to introduce and subsequently maintain a passively safe spacecraft formation. GNC-1 will also be characterized by cross calibration of the SCI instrument suite, particularly with regards to the PLP. After being assured that the GNC control processes are functioning properly and the instruments are prepared to take measurements, the spacecraft will be brought closer together (from $a\delta\lambda \approx 10$ km $\rightarrow a\delta\lambda \approx 3$ km) using the propulsion unit during GNC-2 to further test out the autonomous control abilities of the onboard GNC computer. The ability to schedule maneuvers on top of X-Band downlink periods will also be refined during this time. GNC-1 and GNC-2 are each planned to last ≈1 week.

SCI-<1:3>: DD Expansion 1—The conclusion of GNC-2 will herald the first attempt at the relative accelerometry

[2]The launch date and launch altitude is subject to change, especially as that date approaches.

[3]With each spacecraft operating on the same UHF frequency, SWARM-EX software developers have implemented the robust CCSDS Standard 133.0-B-2 Space Packet Protocol to provide unique data packet identifiers for every end-to-end communication pipeline. In this way, any ground station can uniquely command any of the three spacecraft without concern for the two spacecraft also responding to that command [26].

[4]While the UHF radio is sufficient for the transmission of general spacecraft health/safety information, the immense amount of data generated by the onboard SCI instrument suite and GNC software requires a secondary onboard radio like the Bluefin with significantly faster transmission speeds in order for SWARM-EX to remain "data positive" (i.e., the ability to downlink all data generated to the ground).

experiment discussed previously, the first of many SCI experiments defining the Primary Mission and the beginning of the first expansion of the swarm. By introducing a known differential ballistic coefficient via spacecraft attitude control between the spacecraft of SWARM-EX, the swarm will gradually separate from one another along their orbit as the effects of atmospheric drag impact them differently. In this way, the spacecraft will serve as instruments themselves by realizing an accelerometer in the aggregate from which neutral density in the upper atmosphere can be recovered. The relative accelerometry experiment is only valid while the spacecraft are separated by $a\delta\lambda \leq 250$ km, at which point the variation in thermospheric density experienced by the spacecraft becomes too large. Because the SWARM-EX spacecraft must be separated at large separation distances in order to observe the EIA/ETA at effective spatial/temporal resolutions anyway, SMD-3 is well-suited for the beginning of the expansion.

Due to the nature of the SMD-3 attitude profiles, only the spacecraft in the SMD-3 high drag attitude mode will have the FIPEX operational; all three spacecraft will have the PLP operational. However, once the swarm has reached $a\delta\lambda \approx 250$ km, the SWARM-EX mission designers wish to achieve maximum mean along-track separation as quickly as possible to make time for additional experiments at the end of the mission. This will be achieved by ignoring the pointing constraints of the FIPEX (resulting in powering all units off) and maximizing the differential ballistic coefficient in the swarm (within reason of the power budget) during SCI-<2:3>. The division between SCI-2 and SCI-3 is set at $a\delta\lambda \approx 300$ km as this is the mean along-track separation at which it is predicted the spacecraft will be unable to communicate via the ISL. At these large separation distances, however, this will be a non-issue for the GNC system since conjunctions are highly unlikely. Simulations estimate that the DD portion of the first expansion will last ≈3 weeks.

SCI-<4:5>: PROP Expansion 1—As detailed in Section 2, measurements of the atmosphere relevant to the EIA/ETA are more valuable as the spacecraft approach timescales corresponding to the maximum allowable separation distance imposed by mission requirements. Consequently, once $a\delta\lambda \approx 800$ km, control of the expansion will be handed over to the propulsion unit so that the spacecraft can satisfy the pointing constraints of the FIPEX, which will be turned on for all spacecraft. Recognizing the need to conserve fuel, the propulsive expansion defined by SCI-4 will last ≈10 days. Then, once arriving at $a\delta\lambda \approx 1300$ km, the GNC system will provide very little control of the swarm as each spacecraft takes science measurements for ≈1 month. With the propulsion units disabled to maximize consecutive data capture, the spacecraft will most likely continue to drift apart; setting the boundary of SCI-5 conservatively at $a\delta\lambda \approx 1300$ km assures that the imposed maximum allowable separation boundary is never breached. Completion of the first 100 days of the SWARM-EX mission is expected to be reached during SCI-5.

SCI-<6:9>: Contraction (PROP and DD) 1—SCI-<6:9> is planned to be a mirror of SCI-<1:4> as the swarm contracts back together from its maximum separation distance during the Primary Mission. Just as with SCI-4, SCI-6 will be characterized by fully operational scientific instrument suites and propulsion-based formation reconfiguration. SCI-<7:8> will reflect SCI-<2:3> by continuing the contraction using DD, where the swarm will be expected to close the ISL again during SCI-8. SCI-9 will serve as the counterpart to SCI-1 and yield more data for the relative accelerometry experiment (SMD-3). Simulations estimate that this contraction will take ≈1 month, resulting in a total duration of ≈3 months for the SCI experiments of the Primary Mission. Following SCI-9, the spacecraft of SWARM-EX are expected to be in orbit for ≈140 days.

GNC-<3:4>: New Hybrid Control Scheme—After returning from the large separation distances that characterize SCI-<1:9>, GNC-<3:4> will seek to test an entirely different optimal hybrid control scheme. With the entire science instrument suite disabled to allow for full flexibility in attitude, this scheme will optimize the balance between PROP and DD to achieve a commanded relative spacecraft state. This state will then be evaluated on the ground based on the Δv cost, timeliness, and the accuracy of the states achieved relative to the commanded states. Another iteration of instrument cross calibration will also take place during GNC-3 in preparation for the Extended Mission. GNC-3 and GNC-4 are each planned to last ≈1 week, yielding a prediction of ≈154 days for the Primary Mission in total.

Extended Mission

With an anticipated lifetime of ≈1 year, the SWARM-EX mission designers expect that the spacecraft swarm will successfully complete the Primary Mission with enough time before deorbiting to conduct additional experiments, henceforth referred to as the Extended Mission. The SWARM-EX ConOps gives full priority to the Primary Mission, which has been designed with ample schedule contingency (nearly 50%) given the simulated mission lifetime. Consequently, execution of the Extended Mission requires successful completion of the GNC-<1:2> and SCI-<1:9> and will be evaluated based on the health/status of each spacecraft and if the swarm still orbits in altitude bands which are still relevant to the EIA/ETA. If these conditions are satisfied, the SWARM-EX mission operators will commence SCI-<10:18> and GNC-<5:6>.

SCI-<10:18>: Expansion and Contraction 2—With priority given to obtaining as much data on the EIA/ETA as possible, SCI-<10:18> serves as an exact replica to SCI-<1:9>. While an identical amount of time of ≈90 days is budgeted, the lower altitude of the swarm at this stage is predicted to expedite the differential drag maneuvers. Mission operators will also weigh the advantages of lowering the maximum separation distance from $a\delta\lambda \approx 1300$ km against the deorbiting rate in order to make time for the final GNC experiments. Instrument duty cycles may also be adjusted based on spacecraft power performance in accordance with solar cell/battery degradation.

GNC-<5:6>: Image Capture and SMD-4 (Vertical Gradients)—Following the completion of the second expansion and contraction, the last two weeks of the Extended Mission will be defined by GNC-<5:6>, the two most advanced and zealous experiments of the mission. By utilizing the star tracker of the onboard ADCS, each spacecraft will collect images of other SWARM-EX spacecraft in its field of view at close (GNC-5) and ultra-close (GNC-6) separation distances. The spacecraft will then transmit these images to the ground for post-analysis of vision-based navigation. The complexity of this experiment gives rise to the decision to sequence it near the end of the mission.

Moreover, as the last phase of the extended mission, GNC-6 is also characterized by SMD-4: Vertical Gradients, which seeks to measure the EIA/ETA's spatial and temporal gradients in the radial direction. Since the maneuvers required to realize this particular formation reconfiguration are extremely expensive from a propulsion standpoint, SMD-4 is left to the end of the mission so that enough fuel is preserved for required formation keeping/reconfiguration during the other phases of the mission. This aspect of GNC-6 is therefore an opportunity to use up any remaining fuel before the spacecraft of SWARM-EX fully deorbit in the atmosphere. Following the completion of GNC-<5:6>, the Extended Mission will be complete after a duration of ≈104 days, or ≈258 days in total since Deployment.

6. CONCLUSION

The SWARM-EX mission faces many unique challenges due to its distributed architecture and the complexity of its scientific and engineering objectives. The mission's scientific objectives are intended to address outstanding questions regarding the formation and evolution of the equatorial ionization anomaly (EIA) and the equatorial thermospheric anomaly (ETA), and the extent of the coupling between the two phenomena, while its engineering objectives are focused on advancing the state of the art in CubeSat swarming. The process of overcoming the challenges begins with precisely defining the mission requirements. This is accomplished by formalizing the objectives in terms of Primary Science Questions (PSQs) and Secondary Measurement Demonstrations (SMDs), which are readily translated into requirements for other spacecraft subsystems. The design of the spacecraft themselves proceeds from these requirements, and with an awareness of other constraints on the SWARM-EX mission. The SWARM-EX Autonomous Guidance, Navigation, and Control (SWAG) system enables all SWARM-EX spacecraft to operate independently, and as members of the swarm, by providing absolute and relative orbit estimates based on GNSS and commanding propulsive and differential-drag maneuvers to ensure safety and the accomplishment of the mission's objectives.

A detailed ConOps is developed which must take into account the inherent limitations of CubeSats and the specific challenges faced by SWARM-EX, and which is robust to hardware failures and other on-orbit anomalies. The ConOps is divided into the Primary Mission and Extended Mission. Each of these is characterized by (1) a period of proximity operations, during which the swarm is separated by tens of kilometers in the along-track sense, (2) a period during which inter-spacecraft separation distances are increased to >1000 km, and (3) a return to proximity operations. This expansion-and-contraction cycle is simple and ensures that the most critical objectives are accomplished first, before higher-risk objectives are pursued.

Although this ConOps is unique to the SWARM-EX mission, its successful implementation in orbit has significant implications for future CubeSat missions and formation-flying, generally. In particular, the ability to operate a CubeSat swarm as a distributed sensor both at close range and at enormous scale will mark a major advancement for the field. With an expected launch in Q4 2024, SWARM-EX will soon be providing an exciting and novel contribution to the pantheon of spacecraft formation-flying missions.

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REFERENCES

[1] R. Agarwal, B. Oh, D. Fitzpatrick, A. Buynovskiy, S. Lowe, C. Lisy, A. Kriezis, B. Lan, Z. Lee, A. Thomas, B. Wallace, E. Constantino, G. Miner, J. Thayer, S. D'Amico, K. Lemmer, W. Lohmeyer, and S. Palo, "Coordinating development of the swarm-ex cubesat swarm across multiple institutions," *Proceedings of the Small Satellite Conference*, 2021.

[2] J. Lei, J. Thayer, and J. Forbes, "Longitudinal and geomagnetic activity modulation of the equatorial thermosphere anomaly," *Journal of Geophysical Research: Space Physics*, vol. 115, no. 8, pp. 1–13, 2010.

[3] E. Sutton, J. Forbes, and R. Nerem, "Global thermospheric neutral density and wind response to the severe 2003 geomagnetic storms from champ accelerometer data," *Journal of Geophysical Research: Space Physics*, vol. 110, no. A9, 2005.

[4] B. Tapley, J. Ries, S. Bettadpur, and M. Cheng, "Neutral density measurements from the gravity recovery and climate experiment accelerometers," *Journal of Spacecraft and Rockets*, vol. 44, no. 6, pp. 1220–1225, 2007.

[5] J. Kruger, A. Koenig, and S. D'Amico, "Starling formation-flying optical experiment (starfox): System design and preflight verification," *Journal of Spacecraft and Rockets*, pp. 1–23, 2023.

[6] E. Lightsey, E. Arunkumar, E. Kimmel, M. Kolhof, A. Paletta, W. Rawson, and S. Selvamurugan, "Concept of operations for the visors mission: A two satellite cubesat formation flying telescope," *Proceedings of the AAS Guidance, Navigation, and Control Conference*, 2022.

[7] N. Stacey, K. Dennison, and S. D'Amico, "Autonomous asteroid characterization through nanosatellite swarming," *Proceedings of the IEEE Aerospace Conference*, 2022.

[8] S. Lowe, M. Markevitch, and S. D'Amico, "Relative navigation and pointing error budget for an x-ray astronomy formation-flying mission," *Proceedings of the AAS Guidance, Navigation, and Control Conference*, 2022.

[9] M. Hunter and S. D'Amico, "Closed-form optimal solutions for propulsive-differential drag control of spacecraft swarms," *Proceedings of the AAS/AIAA Astrodynamics Specialist Conference*, 2022.

[10] S. Appleton, "Two anomalies in the ionosphere," *Nature*, vol. 71, no. 3995, p. 3995–3995, 1946.

[11] W. Hanson and R. Moffett, "Ionization transport effects in the equatorial f region," *Journal of Geophysical Research*, vol. 71, no. 23, p. 5559–5572, 1966.

[12] M. Eberhart, S. Löhle, B. Strelnikov, J. Hedin, M. Khaplanov, S. Fasoulas, J. Gumbel, F.-J. Lübken, and M. Rapp, "Atomic oxygen number densities in the mesosphere–lower thermosphere region measured by solid electrolyte sensors on wadis-2," *Atmospheric Measurement Techniques*, vol. 12, no. 4, pp. 2445–2461, 2019.

[13] NovAtel, "Novatel oem719 datasheet," *accessed 3 October 2023*.

[14] ISISpace, "Isispace cubesat antenna system datasheet," *accessed 4 October 2023*.

[15] B. C. Technologies, "Blue canyon technologies attitude control systems datasheet," *accessed 3 October 2023*.

[16] D. Fitzpatrick, E. Bauch, R. Agarwal, , and S. Palo, "Maximizing mission utility within operational constraints for the swarm-ex cubesat mission," *AIAA SciTech Forum*, 2022.

[17] S. D'Amico, "Autonomous formation flying in low earth orbit," *Doctoral Dissertation, TU Delft*, 2010.

[18] J. Sullivan, T. Lovell, and S. D'Amico, "Angles-only navigation for autonomous on-orbit space situational awareness applications," *Proceedings of the AAS/AIAA Astrodynamics Specialist Conference*, 2018.

[19] S. D'Amico and O. Montenbruck, "Proximity operations of formation-flying spacecraft using an eccentricity/inclination vector separation," *Journal of Guidance, Control, and Dynamics*, vol. 29, no. 3, pp. 554–563, 2006.

[20] M. Chernick and S. D'Amico, "New closed-form solutions for optimal impulsive control of spacecraft relative motion," *Journal of Guidance, Control, and Dynamics*, vol. 41, no. 2, pp. 301–319, 2018.

[21] D. Vallado and D. Finkleman, "A critical assessment of satellite drag and atmospheric density modeling," *Acta Astronautica*, vol. 95, pp. 141–165, 2014.

[22] K. Dennison, N. Stacey, and S. D'Amico, "Autonomous asteroid characterization through nanosatellite swarming," *IEEE Transactions on Aerospace and Electronic Systems*, 2023.

[23] V. Giralo and S. D'Amico, "Distributed multi-gnss timing and localization for nanosatellites," *Navigation*, vol. 66, no. 4, pp. 729–746, 2019.

[24] ——, "Precise real-time relative orbit determination for large-baseline formations using gnss," *Proceedings of the International Technical Meeting of the Institute of Navigation*, pp. 366–384, 2021.

[25] S. Lowe and S. D'Amico, "Reduced-order model for spacecraft swarm orbit design," *Proceedings of the AAS/AIAA Space Flight Mechanics Meeting*, 2023.

[26] D. Fitzpatrick, S. Agrawal, S. Palo, N. Rainville, and T. Woods, "Designing a bare-metal flight software architecture for the academic swarm-ex cubesat constellation," *AIAA SciTech Forum*, 2024.

BIOGRAPHY

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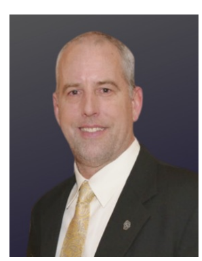
Anton Buynovskiy *is a Ph.D. candidate at the University of Colorado Boulder. He earned a Master of Science degree in Aerospace Engineering Sciences at the University of Colorado Boulder, a Bachelor of Science degree in Mechanical and Aerospace Engineering, and a Bachelor of Arts in Mathematics, at the University at Buffalo. He has served as as the science and instrument lead for SWARM-EX since 2020. His research is focused on ionosphere-thermosphere coupling and the interpretation of measurements from satellite instruments.*

Lillian Shoemaker *is a student at Franklin W. Olin College of Engineering pursuing a Bachelor of Science degree in Mechanical Engineering. Her research with SWARM-EX is focused on the structural design and harnessing of the spacecraft, though she participates in other disciplines, such as hydroponic system design, STEM education, AUV design, and more.*



Scott Palo *is the Charles Victor Schelke Endowed Professor in the Smead Department of Aerospace Engineering Sciences at the University of Colorado Boulder (CU). He has over 20 years of experience in higher education, is the director of the Space Technology Integration Lab, Associate Director of SpectrumX, the first National Science Foundation Spectrum Innovation Initiative Center, and former Associate Dean for Research in the College of Engineering and Applied Science at CU. Dr. Palo conducts research in small satellites, atmospheric remote sensing and the radio frequency spectrum, and is a Fellow of the AIAA and Senior Member of the IEEE.*

Simone D'Amico *(Member, IEEE) received the B.S. and M.S. degrees in aerospace engineering from Politecnico di Milano, Milan, Italy, in 2003, and the Ph.D. degree in Aerospace Engineering from the Delft University of Technology, Delft, The Netherlands, in 2010. He is currently an Associate Professor of Aeronautics and Astronautics (AA), W.M. Keck Faculty Scholar in the School of Engineering, and Professor of Geophysics (by Courtesy). He is the Founding Director of the Space Rendezvous Laboratory and Director of the AA Undergraduate Program. Before Stanford, Dr. D'Amico was research scientist and team leader at the German Aerospace Center (DLR) for 11 years. His research aims at enabling future miniature distributed space systems for unprecedented remote sensing, science, exploration and spaceflight sustainability. His efforts lie at the intersection of advanced astrodynamics, spacecraft navigation/control, and space system engineering. Dr. D'Amico is institutional PI of three upcoming autonomous satellite swarm missions funded by NASA and NSF. He is Fellow of AAS, Associate Fellow of AIAA, Associate Editor of AIAA JGCD, Advisor of NASA and space startups. He was the recipient of several awards, including Best Paper Awards at IAF (2022), IEEE (2021), AIAA (2021), AAS (2019) conferences, the Leonardo 500 Award by the Leonardo da Vinci Society/ISSNAF (2019), FAI/NAA's Group Diploma of Honor (2018), DLR's Sabbatical/Forschungssemester (2012) and Wissenschaft Preis (2006), and NASA's Group Achievement Award for the GRACE mission (2004).*