Coordinating Development of the SWARM-EX CubeSat Swarm Across Multiple Institutions

SSC21-WKI-02

Session: Coordinating Successful Educational Programs

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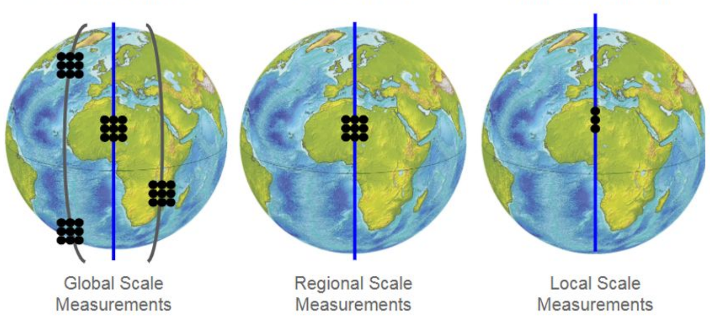
Outline

1. SWARM-EX Mission Introduction
2. SWARM-EX Science Objectives
3. SWARM-EX Technical Objectives
4. Distributed Team Collaboration and Communication
5. SWARM-EX Testing Plans
6. Education and Public Outreach
7. Future Work and Next Steps

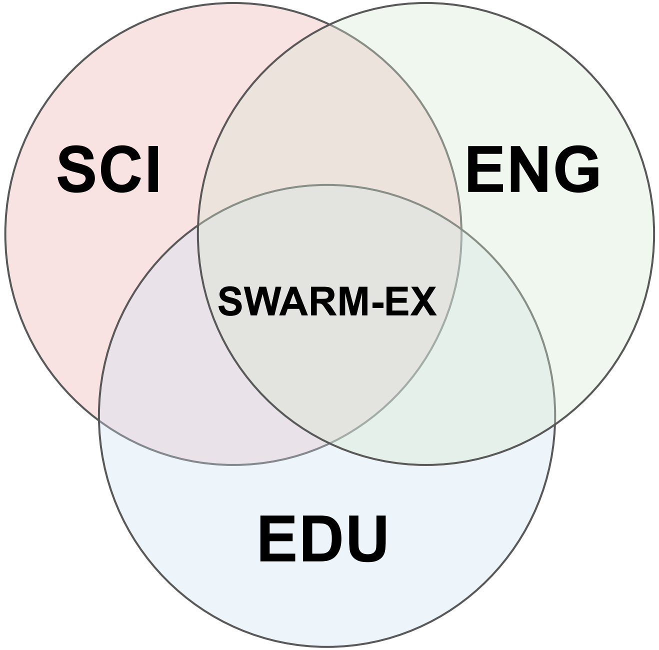
SWARM-EX Introduction

- Complex technical program
  - Demonstrate autonomous and reconfigurable formation flying with more than two spacecraft for the first time
  - Proof of concept for future aeronomy experiments
- Distributed program presents challenges
  - Communication and collaboration among six institutions
  - Distribution of hardware, equipment, and facilities
  - Varying levels of experience



SWARM-EX is a scientific mission consisting of a trio of 3U CubeSats (rightmost image) that will demonstrate autonomous swarm technologies that can eventually be scaled to single swarms of larger sizes (center) and multiple swarms operating in different orbits (left).

Mission Goals



- Persistence and correlation in EIA/ETA features
- Changes in EIA/ETA features that occur over timescales of less than 90 minutes

- Formation flying
- Collision avoidance
- Detach & reconnect
- Propulsion
- UHF crosslink
- CDMA downlink

- Intercollegiate CubeSat Mentoring Program
- CubeSat Questions Slack channel
- Efforts to track student engagement/progress

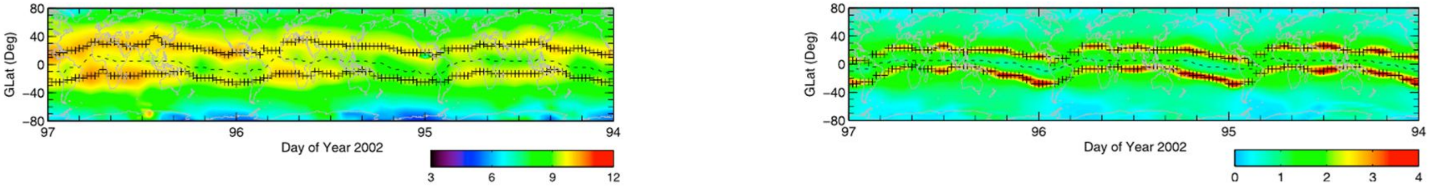
Science Objectives

Primary science questions deal with the equatorial Ionosphere-Thermosphere (I-T) region

- How persistent and correlated are the plasma density and neutral oxygen in Equatorial Ionization Anomaly (EIA) and Equatorial Thermospheric Anomaly (ETA) features?
- Over what timescales, less than 90 minutes, do we observe changes in EIA/ETA properties due to non-migrating tides and geomagnetic activity?

Secondary science mission demonstrations include

- Instrument cross-calibration
- Observing small scale plasma perturbations
- Estimating mass density using measurements of relative motion
- Measuring small vertical gradients in neutral and plasma density



Neutral Mass Density (top) and Electron Density (bottom) showing the ETA and EIA respectively from data taken by the CHAMP satellite at 400 km altitude. Graphs taken from Lei et al.

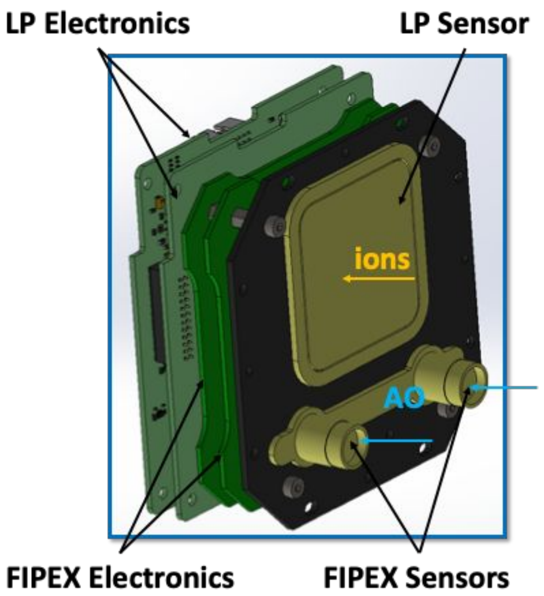
Science Instruments

Onboard in-situ instruments (ram-facing)

- Langmuir Probe:
  - Will measure the ion density (O^+ being the main constituent) in the EIA
- FIPEX:
  - Will measure Atomic Oxygen (main neutral atom) concentrations in the ETA

Relevance

- Atomic Oxygen
  - Oxidizes materials
  - Atom collisions damage ram-facing surfaces of spacecraft in LEO
  - Main contributor to orbital drag as it is the dominant neutral species
- O^+ (and its concomitant electron density population)
  - Electron charge buildup on a spacecraft can affect instruments sensitive to spacecraft potential
  - Electric charge buildup can cause differential charge that can arc and damage a spacecraft
  - Electron density in LEO can prevent a GPS receiver from locking onto a signal



SWARM-EX science payload

Engineering Objectives

SWARM-EX will advance the state of the art in spacecraft formation flying in several key ways

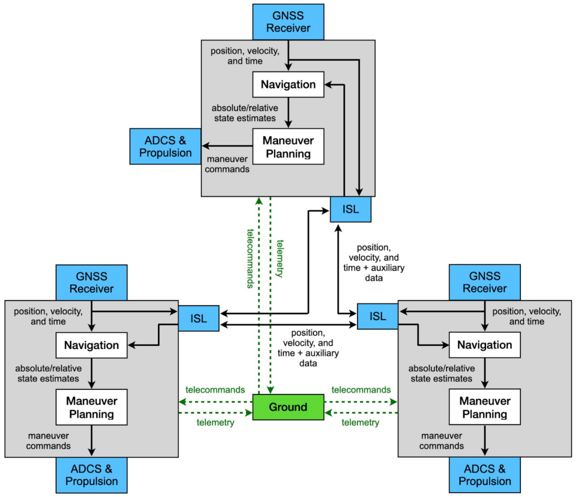
- First demonstration of passively safe, autonomous formation flying for more than two spacecraft
- Will utilize a novel hybrid propulsive/differential-drag control scheme
- Will achieve fuel balancing among the spacecraft in the formation using a virtual chief method
- Will realize a distributed aeronomy sensor

Relative accelerometry experiment:

- Spacecraft attitudes modulated to maximize differential ballistic coefficient and sensitivity to atmospheric drag
- Precise relative state estimates provided by the Distributed multi-GNSS Timing and Localization (DiGiTaL) system then used to recover atmospheric density through relative spacecraft acceleration

Formation Flying Methodology

- Spacecraft exchange position, velocity, and time (PVT) solutions from onboard GNSS receivers via UHF inter-satellite link (ISL), allowing estimation of absolute state and relative states with respect to other spacecraft in the formation
- Passive safety achieved using method of relative e-/i-vector separation
- Hybrid propulsive/differential drag-based control used to realize large along-track reconfigurations that are needed to meet the science objectives
- Spacecraft downlink raw GNSS measurements to ground segment. Raw measurements are processed in the state-of-the-art DiGiTaL estimation framework, enabling centimeter-level relative navigation accuracy.



SWARM-EX onboard guidance, navigation, and control (GNC) architecture

Collaboration Across Varied Institutions

- Varying levels of institutional CubeSat experience
  - Three universities have significant CubeSat experience (Stanford, CU, GT), three have new CubeSat programs (USA, Olin, WMU)
- Varying levels of student experience
  - Students range from first year undergraduates to Ph.D. students
- To build experience across all institutions, each school is leading the development of at least one subsystem, and many subsystem teams have membership from at least two institutions
  - CU → Olin, USA
  - GT → WMU
  - Stanford → resource to all other institutions for GNC

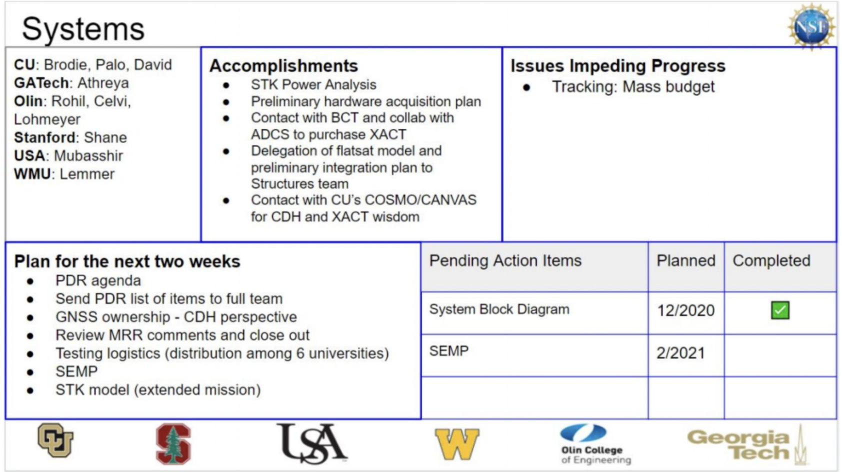
Remote Communication Strategies

Real-time (via Zoom/WebEx)

- Biweekly All-Hands Meeting (cross-university)
  - Present subsystem quad charts
  - Discuss high-level issues
- Biweekly Subsystem Meetings (cross-university)
  - Discuss subsystem-level issues
- Weekly Internal Meetings (intra-university)
- Biweekly Seminar Series (cross-university)
  - Promote team culture by discussing topics of shared interest

Asynchronous

- Slack workspace



An example "quad chart" slide brought to the biweekly all-hands meeting.

Digital Tools for Collaboration

Google Drive

- Shared drive hosted by CU Boulder
- Disadvantages
  - By July 2022, Google will no longer be providing unlimited storage space to the academic community
  - Does not support version control well
    - Currently mitigated by document release procedure

GitLab

- Open-source collaboration platform that provides features like agile planning, version control, and code review, as well as built-in security
- Must be accessed via CU's internal Virtual Private Network (VPN), which only CU students have access to
- Process for non-CU team members to become a CU person of interest, a network status that provides them with VPN login credentials

Distributed Testing Plans

All SWARM-EX students should have the opportunity to gain experience in developing and testing physical hardware regardless of their institution. However, this presents some challenges:

- Varying facilities, equipment, and staffing among the different schools
- Shipping hardware between institutions during different phases of I&T would increase program costs and introduce significant risk of damaging flight hardware

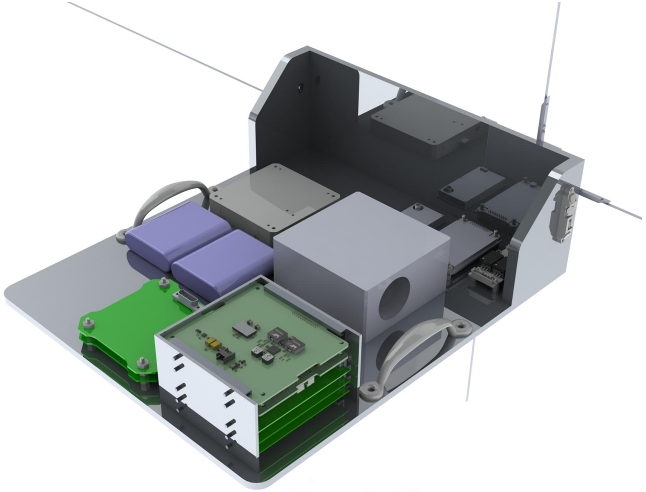
CU has been chosen as the location where the majority of testing will be completed. Some functional testing will be performed at the institutions managing the respective subsystems, including

- Testing of GNC algorithms at Stanford on non-SWARM-EX testbeds
- Propulsion system testing at GT prior to shipment and at WMU after delivery
- Electronic loads testing on the electrical power system (EPS) circuit boards at USA
- Testing of secondary ground stations located at Olin and USA

Each institution will be responsible for developing testing plans for their subsystems. They will then support the implementation of their plans remotely or, if logistics allow, by traveling to CU.

FlatSat Testing

- Development of CAD model and associated assembly plans is led by Olin students
- Components were selected for inclusion in the FlatSat in collaboration with team members at the various SWARM-EX institutions
- FlatSat ownership will transition to CU students for physical assembly, testing, and integration of components, while the assembly and test procedures for the subsystems will be written by the respective subsystem teams at all institutions
- Remote access to the integrated FlatSat testbed is available in a limited capacity to students outside of the physical lab space via VPN



Rendering of assembled SWARM-EX FlatSat as of May 2021.

Education and Public Outreach

Cross-Institutional Mentoring

- Experienced programs and students naturally serve as mentors to less experienced programs and students on the same subsystem teams
- The experiences and practices of the well-established programs immediately become founding principles in the new programs

CubeSat Questions Slack Channel

- Gives students access to members of experienced CubeSat teams and content experts in all areas of CubeSat development, including launch, operations, I&T, EPS, structures, communications, propulsion, and GNC
- Provides a personalized experience where a detailed, direct answer can be received from a context expert
- Could serve as a tool for advertising academic activities such as lectures or webinars
- 110 total members as of May 2021 from 16+ universities around the world, remains open for new members to join

Team Member Surveys

- Entry, annual, exit, and demographic surveys to track the effectiveness of the SWARM-EX educational program in developing students’ interests and skills

Looking Ahead

Timeline

- Currently in Phase C (final design and fabrication) according to the NASA Project Life Cycle
- August 2020: Mission Concept Review (MCR)
- February 2021: Preliminary Design Review (PDR)
- September 2021: Critical Design Review (CDR)
- After CDR: complete all integration and testing, with a Pre-I&T Review (PITR), a Pre-Environmental Review (PER), and a Pre-Shipment Review (PSR) scheduled for 2022 and early 2023
- Mid 2023 to Early 2024: Launch

Approaching CDR

- Hardware testing on individual components and systems
- Closing contracts for a variety of commercially-produced components
- Fabricating multiple versions of the CubeSat structure through iterative design

Beyond SWARM-EX

SpectrumX proposal for the NSF-sponsored Spectrum Innovation Initiative: National Center for Wireless Spectrum Research (SII-Center)

- Submitted April 2021
- Includes the SWARM-EX faculty leads from CU and Olin