The PY4 Mission:
A Low-Cost Demonstration of Multi-CubeSat Coordination

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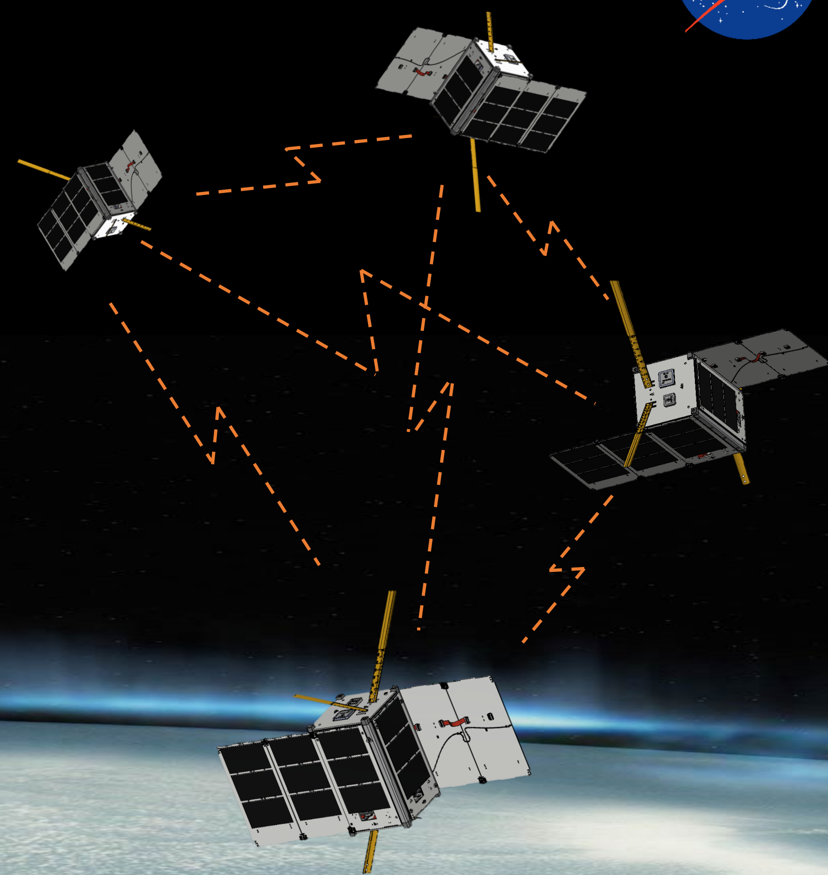
PY4 demonstrates RF-based swarm coordination



1. **Verification of S-band ranging <1 m** precision (distances >500 km*)
2. **Coordinated radiation measurements**
3. **On-orbit relative** & absolute* **position determination**
4. **OTA software** & firmware* **update and mesh forwarding**
5. **3-axis MT-only sun-pointing demonstration**
6. Drag-only station keeping*

**Extended mission demonstration*

PY4 responds to multiple NASA relevant technology development disciplines

NASA Technology Taxonomy	PY4 Relevancy
TX02 Flight Computing and Avionics *TX02.1 Avionics Component Technologies* *TX02.2 Avionics Systems and Subsystems* *TX02.3 Avionics Tools, Models, and Analysis*	• PyCubed Avionics development • Demonstration of Low SWaP-C Chip-scale technologies
TX05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems *TX05.2 Radio Frequency* *TX05.3 Internetworking* *TX05.4 Network Provided Position, Navigation, and Timing*	• Development of RF-based swarm mesh networking among 4 satellite nodes • RF-based ranging and on-orbit relative position determination
TX08 Sensors and Instruments *TX08.1 Remote Sensing Instruments/Sensors* *TX08.2 Observatories* *TX08.3 In-Situ Instruments and Sensors*	• Demonstration of coordinated multi-point radiation measurements of SAA
TX10 Autonomous Systems *TX10.1 Situational and Self Awareness* *TX10.2 Reasoning and Acting* *TX10.3 Collaboration and Interaction*	• OTA flight software update and autonomous forwarding • Relative positional determination relative to chief • Store and forwarding autonomous pointing demo commands

NASA Technology Taxonomy	PY4 Relevancy
TX11 Software, Modeling, Simulation, and Information Processing *TX11.1 Software Development, Engineering, and Integrity* *TX11.2 Modeling* *TX11.3 Simulation* *TX11.4 Information Processing* *TX11.5 Mission Architecture, Systems Analysis and Concept Development* *TX11.6 Ground Computing*	• Verification and improvement of radiation models • Verification of swarm modeling • Verification of relative positioning algorithms
TX17 Guidance, Navigation, and Control (GN&C) *TX17.2 Navigation Technologies* *TX17.3 Control Technologies* *TX17.4 Attitude Estimation Technologies* *TX17.5 GN&C Systems Engineering Technologies*	• Advanced calibration techniques for pointing demo • Experimental MT-only pointing controller • Rel nav positioning

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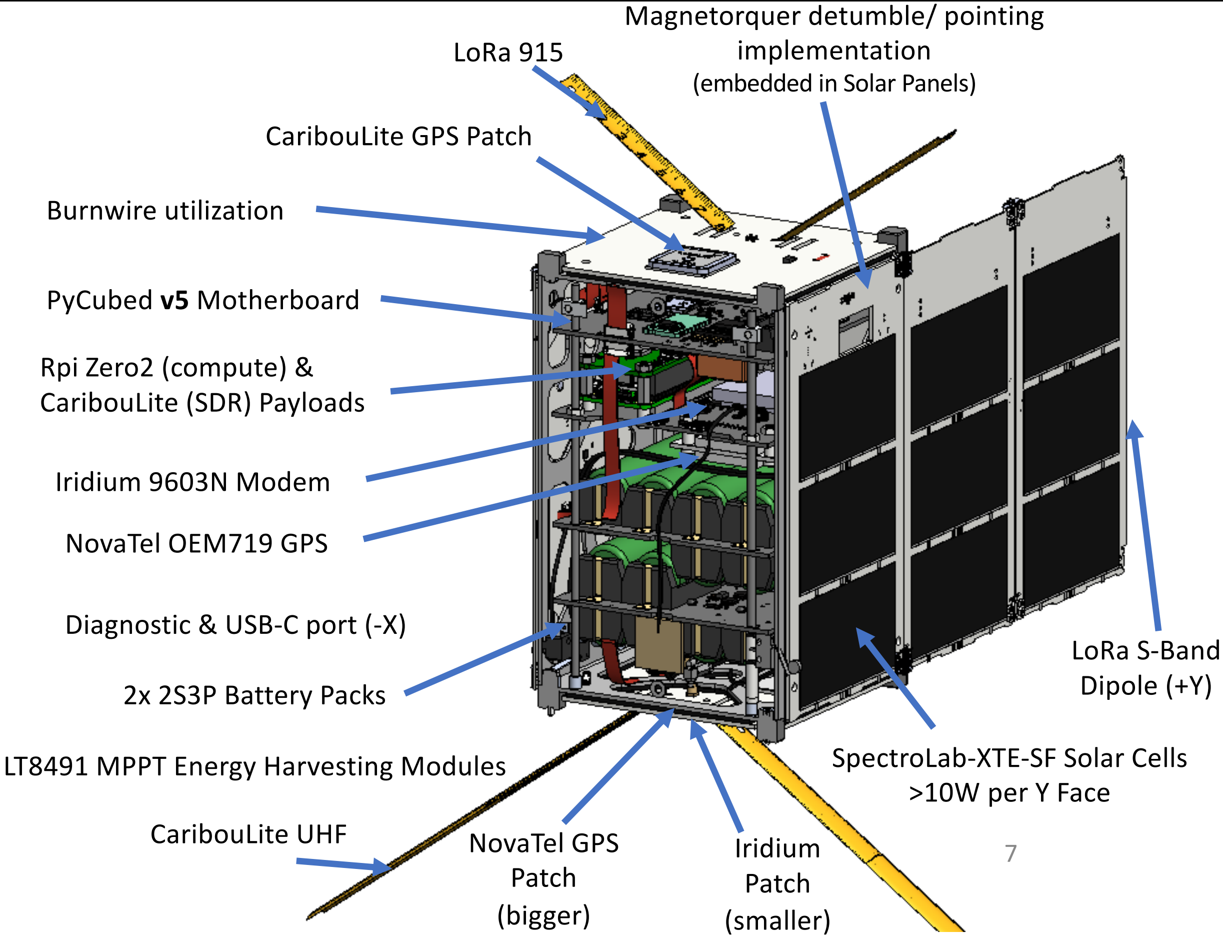
PY4 consists (mostly) of RF payloads run by a PyCubed flight computer



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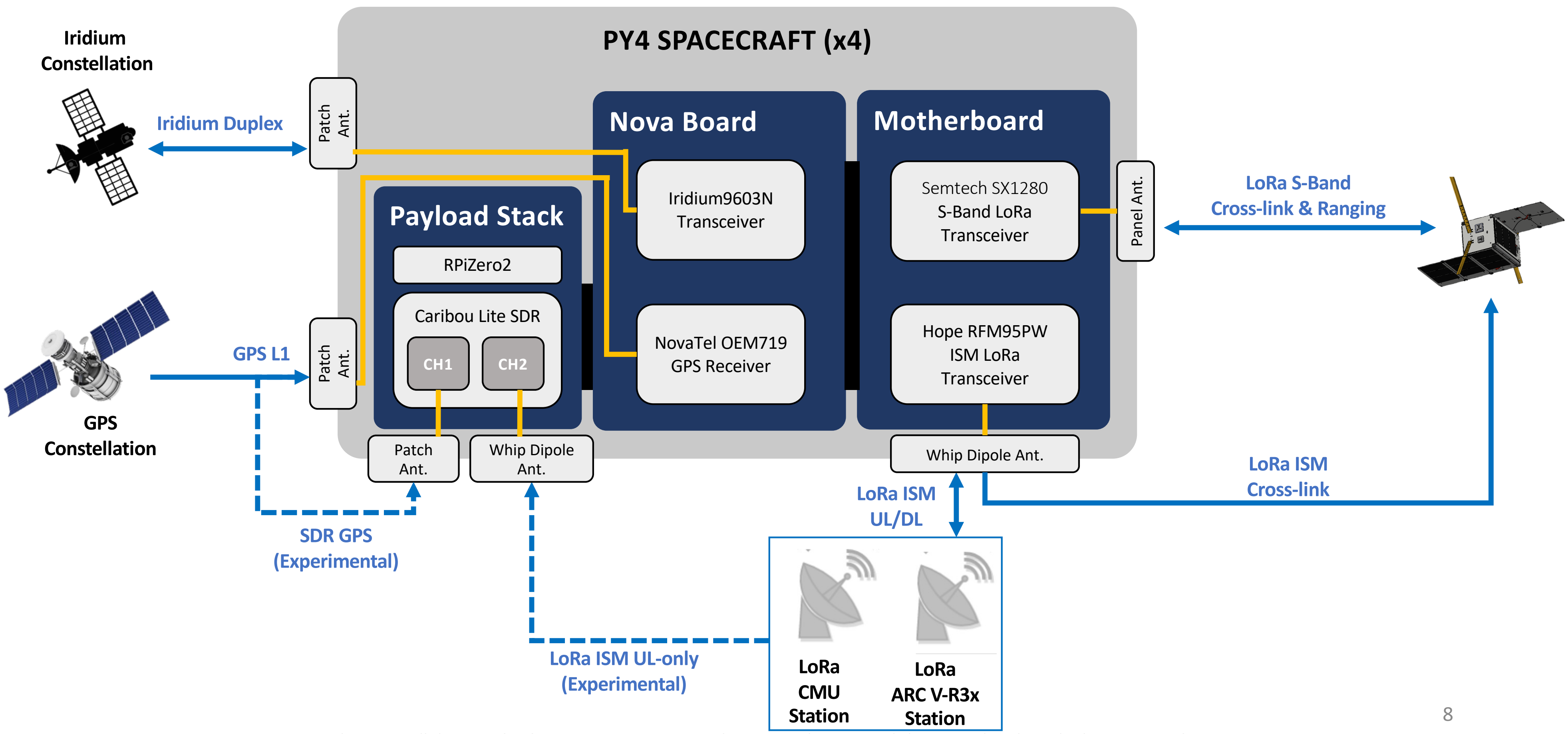
<u>**Four**</u> 1.5U CubeSats

Advanced mesh network

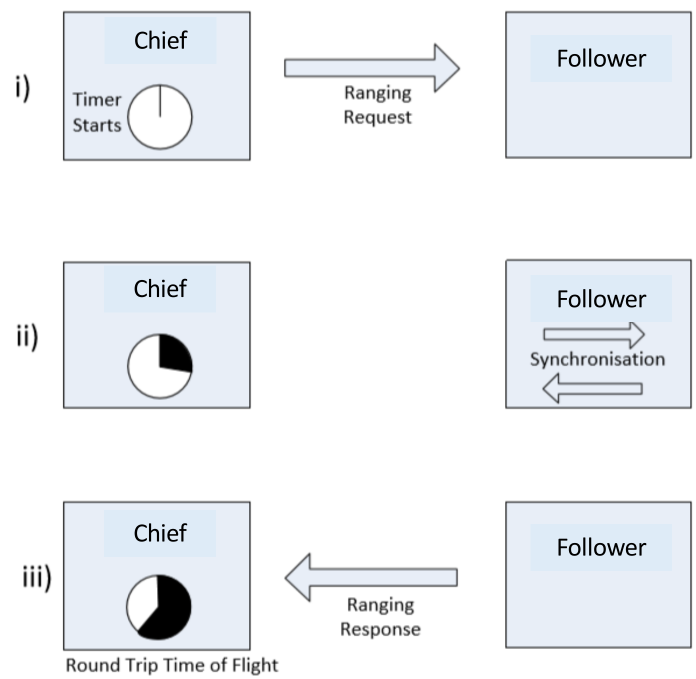
Communications Subsystem supports RF ranging experiments and telemetry downlinks



Ranging Demo utilizes COTS LoRa chirp modulation

- Chirp modulation is ideal for time-of-flight ranging
- Newest S-band LoRa chips have ranging functionality built into the hardware
- Ranging is performed between four spacecraft
- GPS data will be logged during ranging experiments for ground-truth

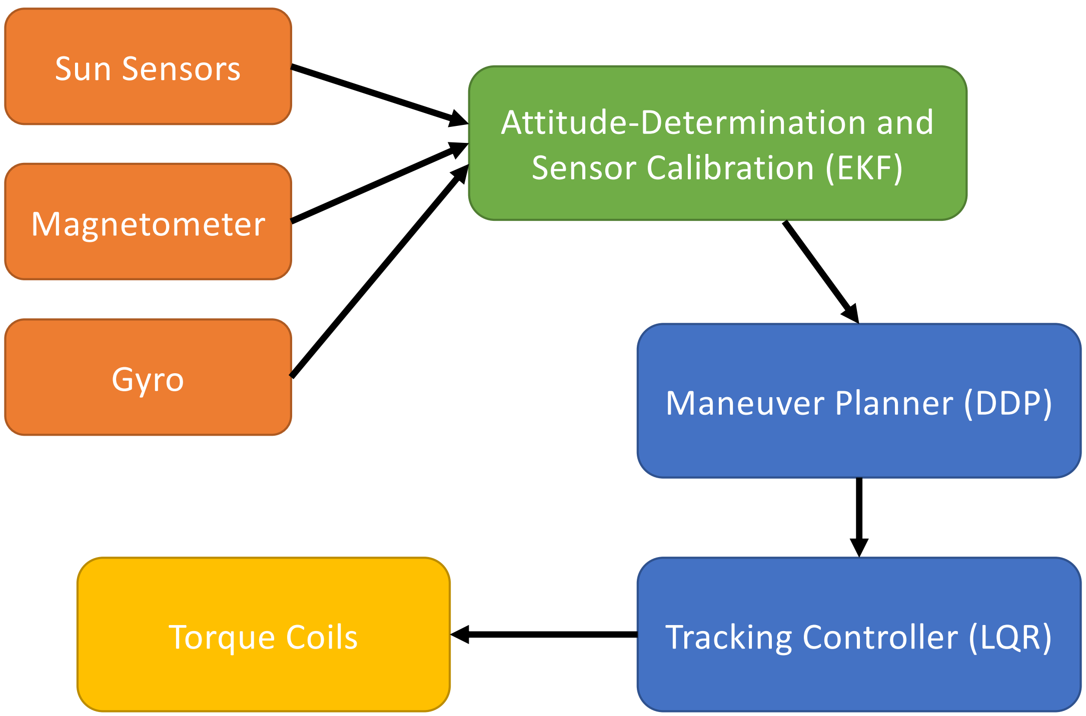
Time of flight ranging process

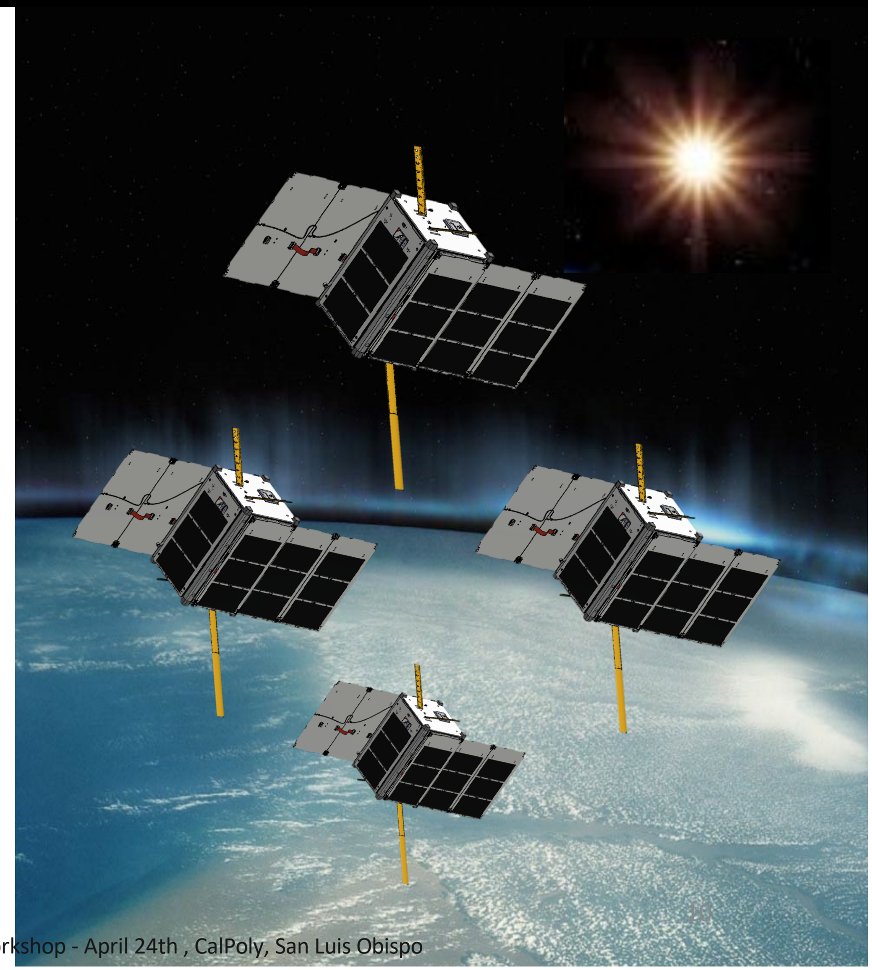


<u>Ranging Packet Format</u>

Preamble	Double Header	Ranging Request	Ranging Silence	Ranging Response
16,25 Symbols	16 Symbols	15 Symbols	2 Symbols	15 Symbols

3-Axis Magnetorquer Pointing algorithms implement a-priory knowledge of the magnetic field





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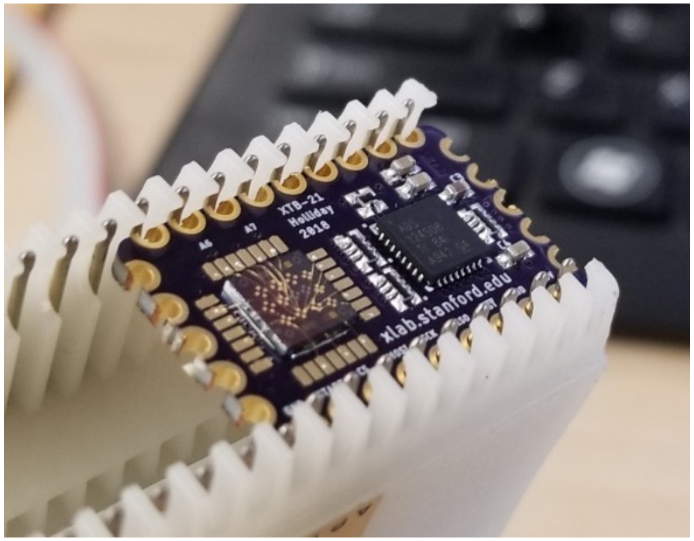
Coordinated Radiation Measurements implemented between 4 spacecraft

- The South Atlantic Anomaly (SAA) is an area where the Earth's inner Van Allen radiation belt comes closest to the Earth's surface, dipping down to an altitude of 200 km
  - *This leads to an increased flux of energetic particles in this region and exposes orbiting satellites to higher-than-usual levels of radiation*
- **Distributed total ionizing dose measurements of the SAA have never been mapped in-situ before**
  - In-situ distributed measurements will be able to differentiate spatial from time-based gradients of the South Atlantic Anomaly

PY4 will complete this demonstration

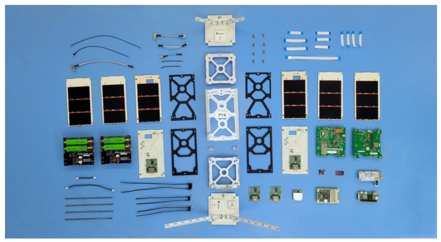
  - Radiation measurements were taken from V-R3x but were not able to be downloaded due to power anomaly

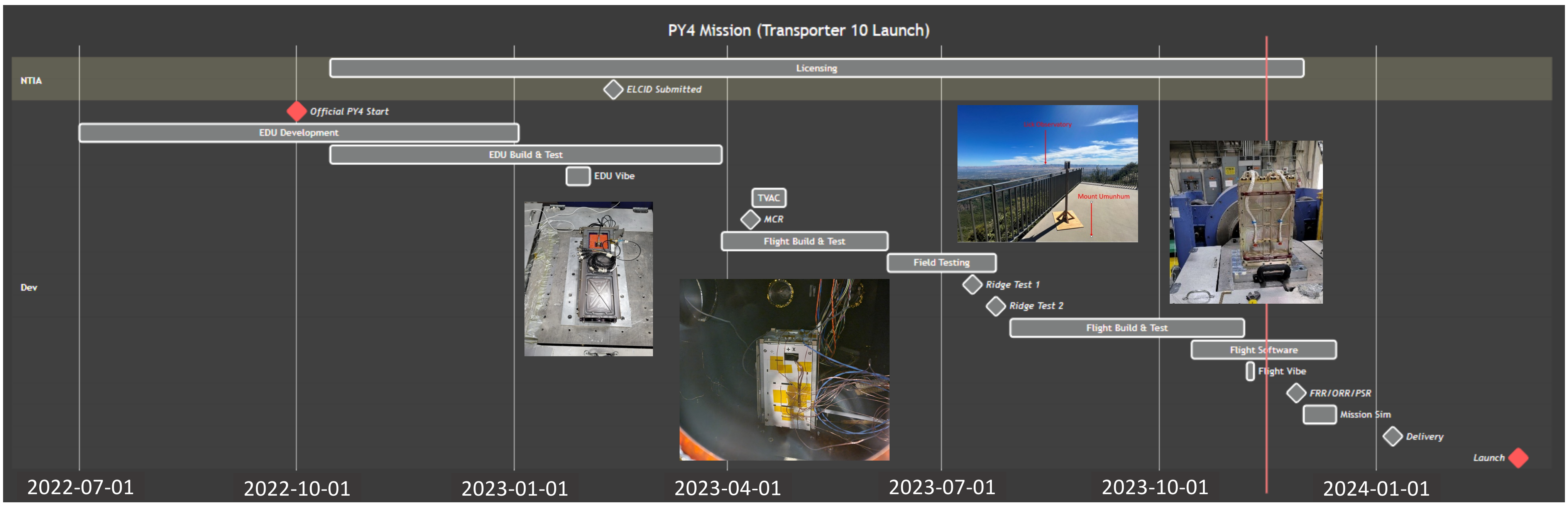


RADFET to measure radiation

Existing modular in-situ radiation measurement platform. Previously validated at Ames BioSentinel Gamma Radiation Facilities

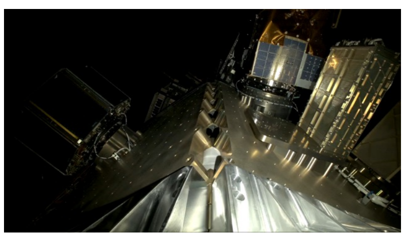
I&T included early vibe and TVAC testing of EDU hardware, and RF field tests

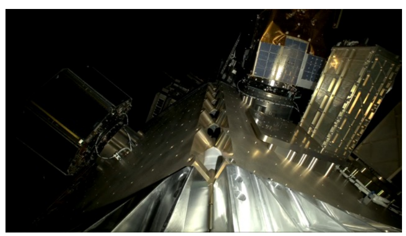
4 x  = 



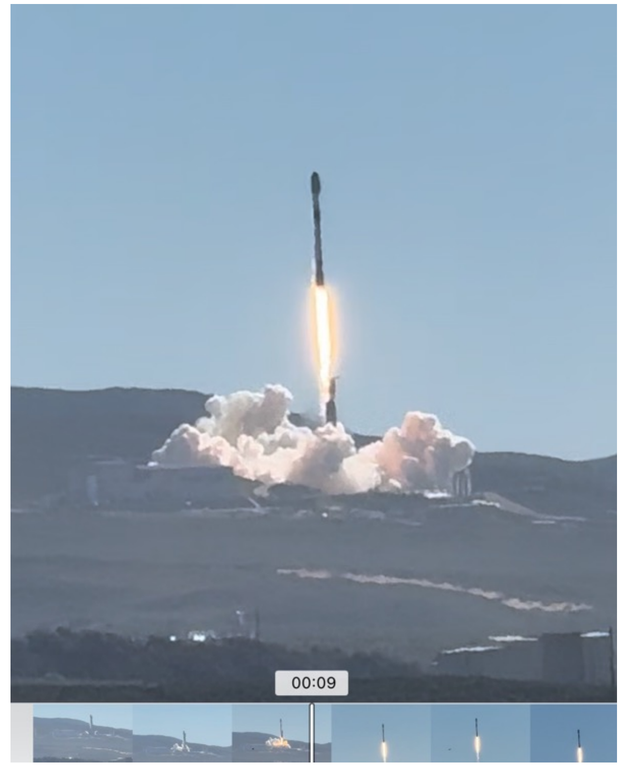
PY4 launched March 04 2024 on SpaceX T-10

- Space-X Transporter-10
- Launch Date: 04 March 2024
- Altitude: **525 km**
- Inclination: **SSO 97.5 deg**
- Launch Service Provider: Maverick Space Systems, Inc. of San Luis Obispo





Source: SpaceX via Maverick Space Systems



Source: Roger Hunter - NASA

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Concept Of Operations

Eject from Dispenser (two sets of two) → **Separation & Deployment** → **Nominal Operations**

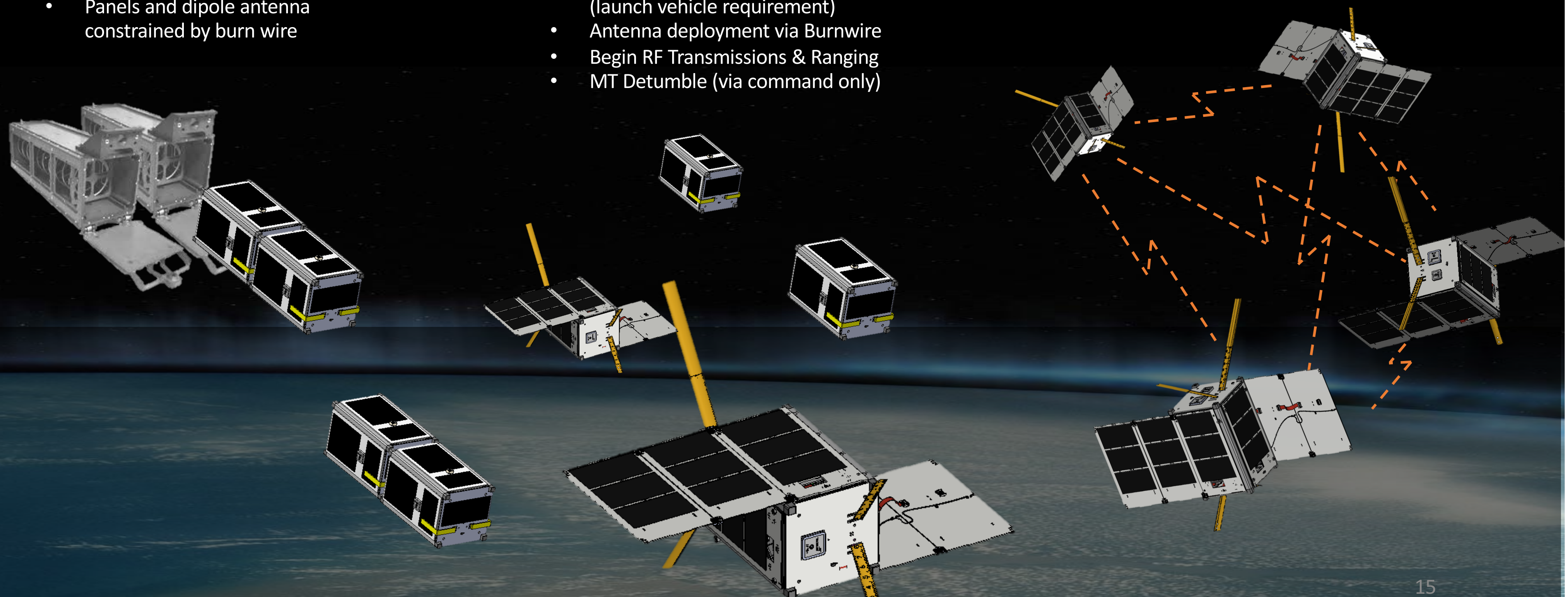
Eject from Dispenser (two sets of two)

- SC untethered
- Panels and dipole antenna constrained by burn wire

Separation & Deployment

- Wait 30 sec (launch vehicle requirement)
- Antenna deployment via Burnwire
- Begin RF Transmissions & Ranging
- MT Detumble (via command only)

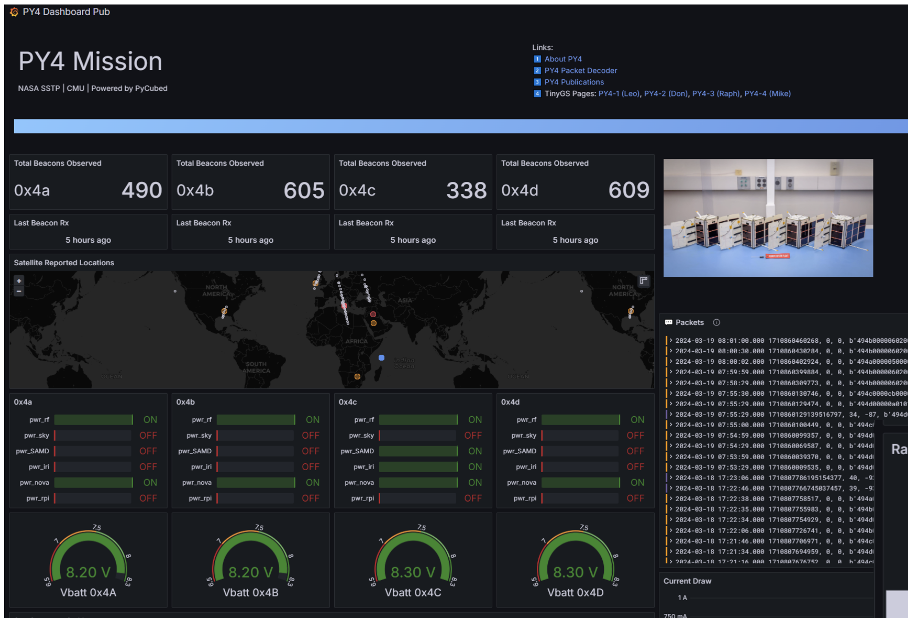
Nominal Operations

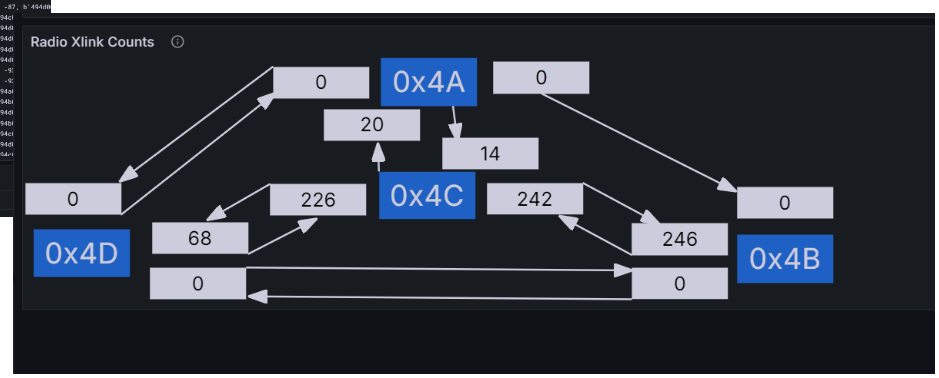


PY4 L1 Tech Demo **Threshold** Requirements

ID	Short description	Requirement Description	Verification & Validation	Required # of SC
L1-001 ✓	S-band High Precision Ranging	PY4 shall demonstrate ranging with <1 m precision at a distance of at least 10 km between at least two satellite nodes	Orbit determination ground tool with inputs from spacecraft GPS and CSPoC TLEs.	2
L1-002 ✓	Relative On-orbit Position determination	PY4 shall demonstrate on-orbit relative positioning between all satellite nodes using ranges-only to an accuracy of 100 m (1-sigma)	Orbit determination ground tool comparison between SC ranging inputs and inputs from spacecraft GPS and CSPoC TLEs. ***Note:*** *Algorithms based on Helioswarm architecture. Helioswarm is processing the relative position on the ground; PY4 will processing the relative position on-orbit*	2
L1-003 ✓	Distributed sensor collection	PY4 shall coordinate and collect at least one radiation data packet from on-board sensors from each satellite node	Compare to simulated + terrestrial sensor data	2
L1-004 ✓	OTA Software Update	PY4 shall perform an over-the-air software update software on at least one satellite node w/ autonomous updates to at least one other satellite node	Spacecraft telemetry downlink from satellite nodes. *Note: Demonstrates the flexibility & utility of having a Python real-time interpreted language as flight software*	2
L1-005 ✓	Wheel-less 3-axis (Magnetorquer-only) Pointing	PY4 shall demonstrate 3-axis magnetorquer-only sun-pointing on at least one satellite node to an accuracy of ±10 deg (1-sigma)	Verify slew rate and pointing accuracy with Sun sensor readings; *Note: pointing accuracy is limited by angle sensitivity of the sun sensor.*	1

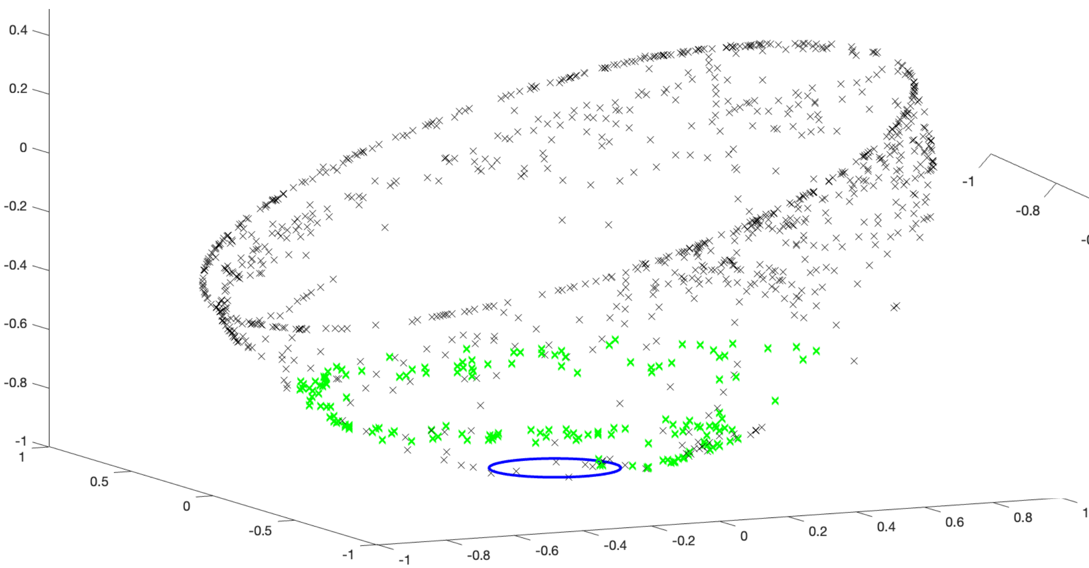
PY4 successfully exchanged ranging packets

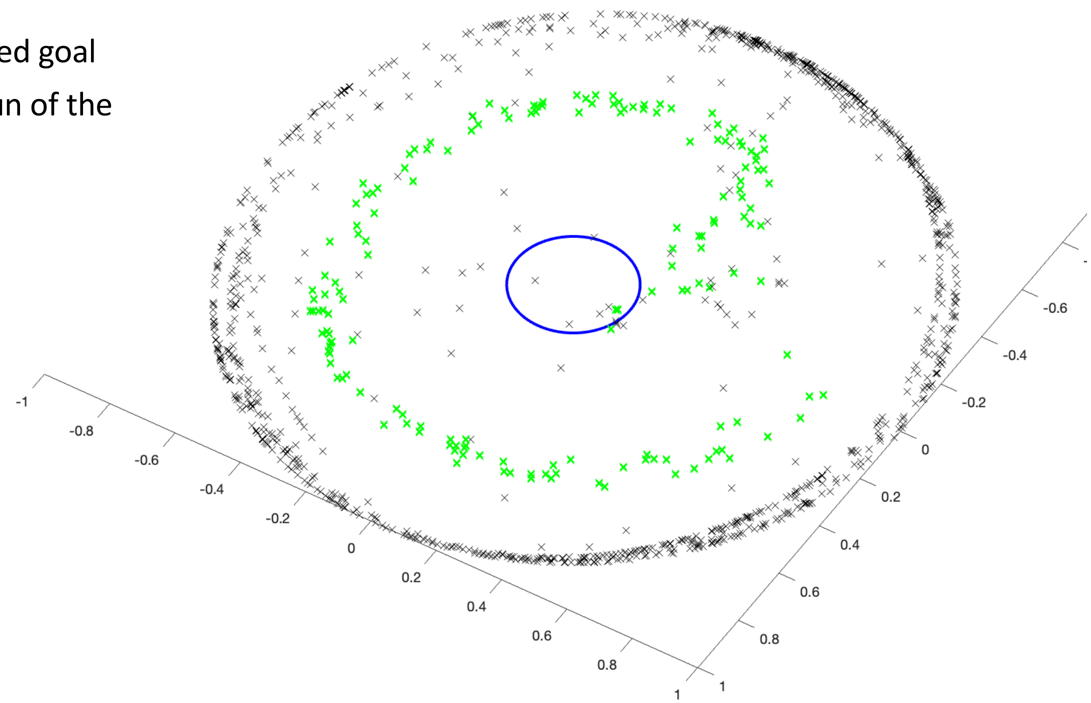




PY4 demonstrated magnetorquer Sun Pointing

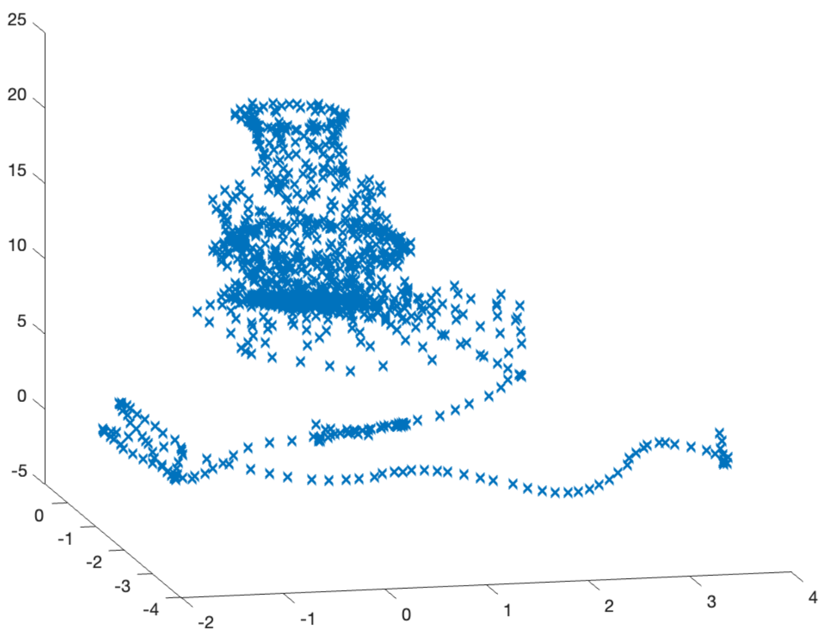
- Novel magnetorquer-based controller points largest solar panels at the sun
- Plots show sun unit vector in the spacecraft body frame
- Solid blue circle indicates 10 deg error bound around the desired goal
- Green samples collected at 5Hz from sun sensors during last run of the controller demonstrates convergence to the goal region

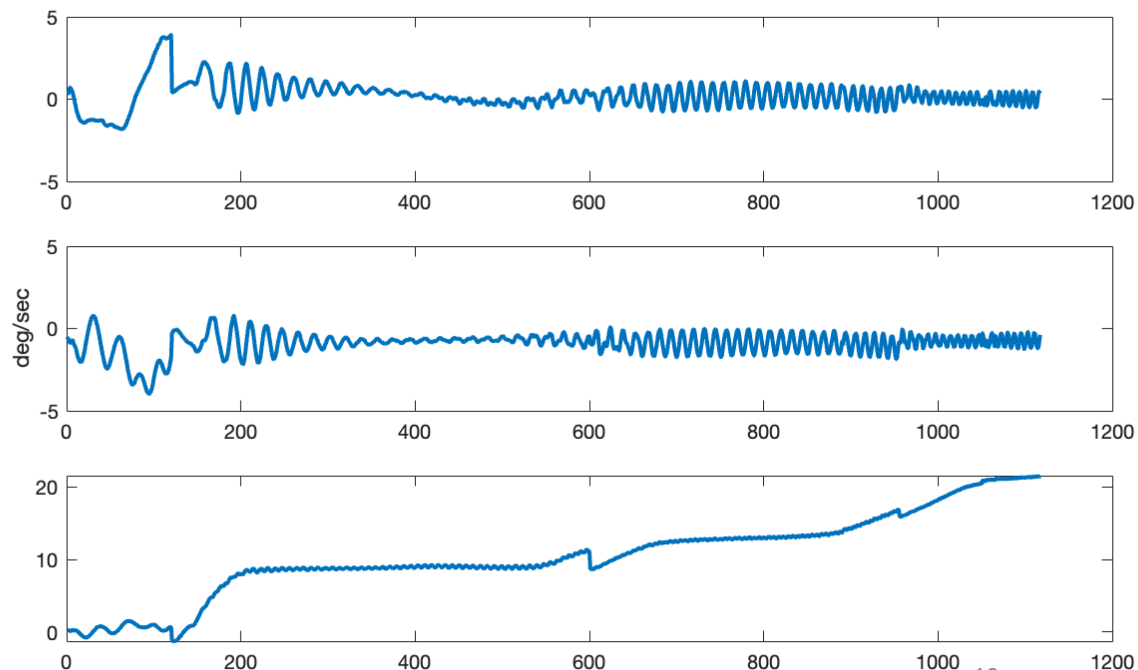




PY4 demonstrated magnetorquer initiated Spin Stabilization

- Magnetorquer-based controller puts the spacecraft in a passively stable flat spin
- This maneuver can be performed faster and more reliably than detumbling
- Plots show 3-axis gyro data recorded during maneuver
- Spacecraft goes from tumbling at several deg/sec to a stable spin about the z-axis at 20 deg/sec with minimal nutation





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PY4 Conclusions

- PY4 primarily focuses on onboard autonomous navigation and control algorithms and applying lessons learned from V-R3x and V-R3x suborbital demonstrations
- Range-based navigation technique provides a low Swap-C alternative to optical rel-nav strategies
  - Same navigation architecture as Helioswarm (mother + daughters) and similar GNC algorithms
- Demonstration of magnetorquer-only pointing could provide fallback option to recover from failed reaction wheels for future missions
- Demonstration of reliable OTA software updates to extend the useful life of SmallSats
  - Extended mission demonstration of OTA Software updates to includes enabling of out-of-family inter-spacecraft communication
- Continues development and advances capabilities of PyCubed open-source avionics stack
  - Reduces barriers to entry, enables low SWaP-C and fast mission development timelines
  - High impact: being used by many university teams and first-time CubeSat developers

Thank you

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  - NASA Ames
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