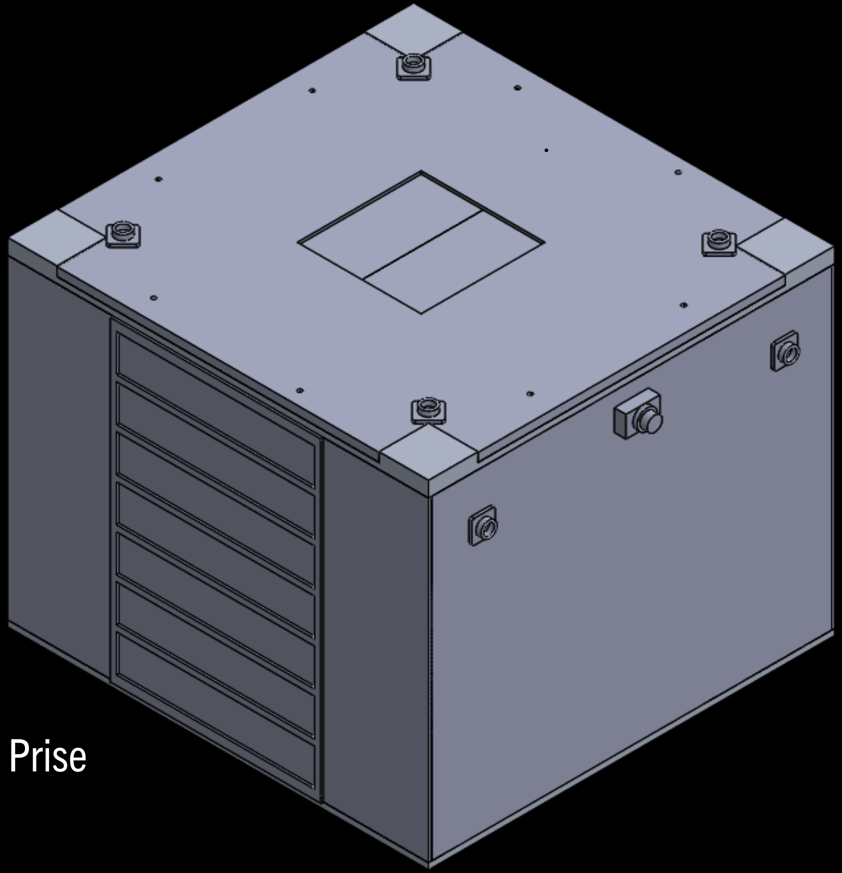
C3 COMPETITION BRIEF-OUT



SCCRAM Jet

Penn State University

Students: Aidan McGrath, Christian Bouarouy, Coral Lee, Maddy Kinevy, Sophia Kotzen, Ryan Prise

Advisor: Dr. Sara Lego

Mentor: Dr. Ed Tate

April 14, 2025

TEAM

SCRAMM Jet

COSMIC
CONSORTIUM FOR SPACE MOBILITY AND ISAM CAPABILITIES

Christian Bouarouy
Command & Data Handling

Maddy Kinevy
Systems Engineering, Structures

Sophia Kotzen
Power

Coral Lee
Communications, CAD

Aidan McGrath
Propulsion, Orbital Mechanics

Ryan Prise
Thermal

EXECUTIVE SUMMARY

SCRAMM Jet – Final Payload Design

Problem: A satellite's lifespan is limited to the longevity of its internal components.

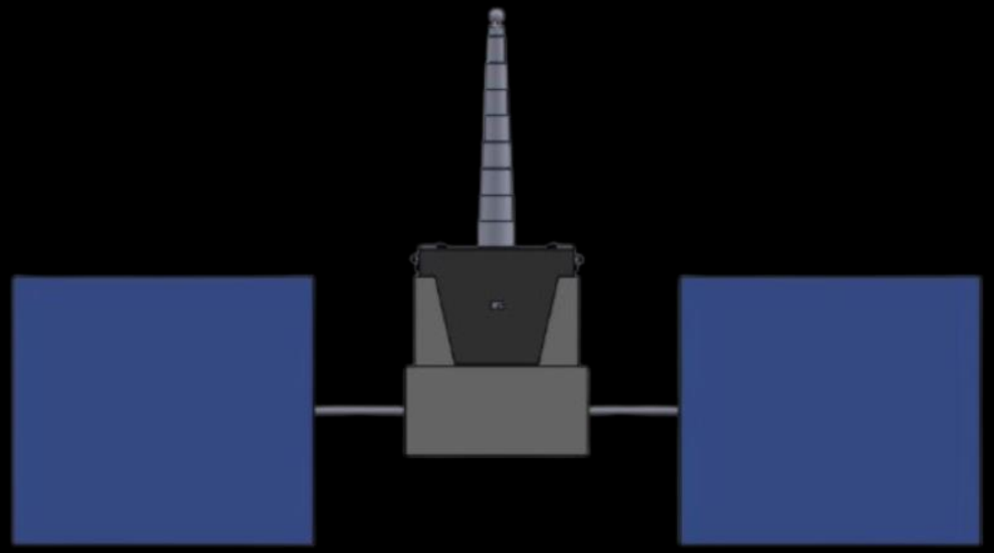
Status: Missions exist to repair physical components; none have successfully repowered an on-board battery by induction.

Capability: The SCCRAM Jet mission aims to recharge the battery of a low-power satellite using induction charging.

Solution: Recharging an existing satellite, rather than relaunching, will allow organizations to save time, money, and labor while practicing sustainable operations.

Autonomous Operations:

1. Rendezvous with target satellite.
2. Docking with Target Satellite.
3. Induction charging.



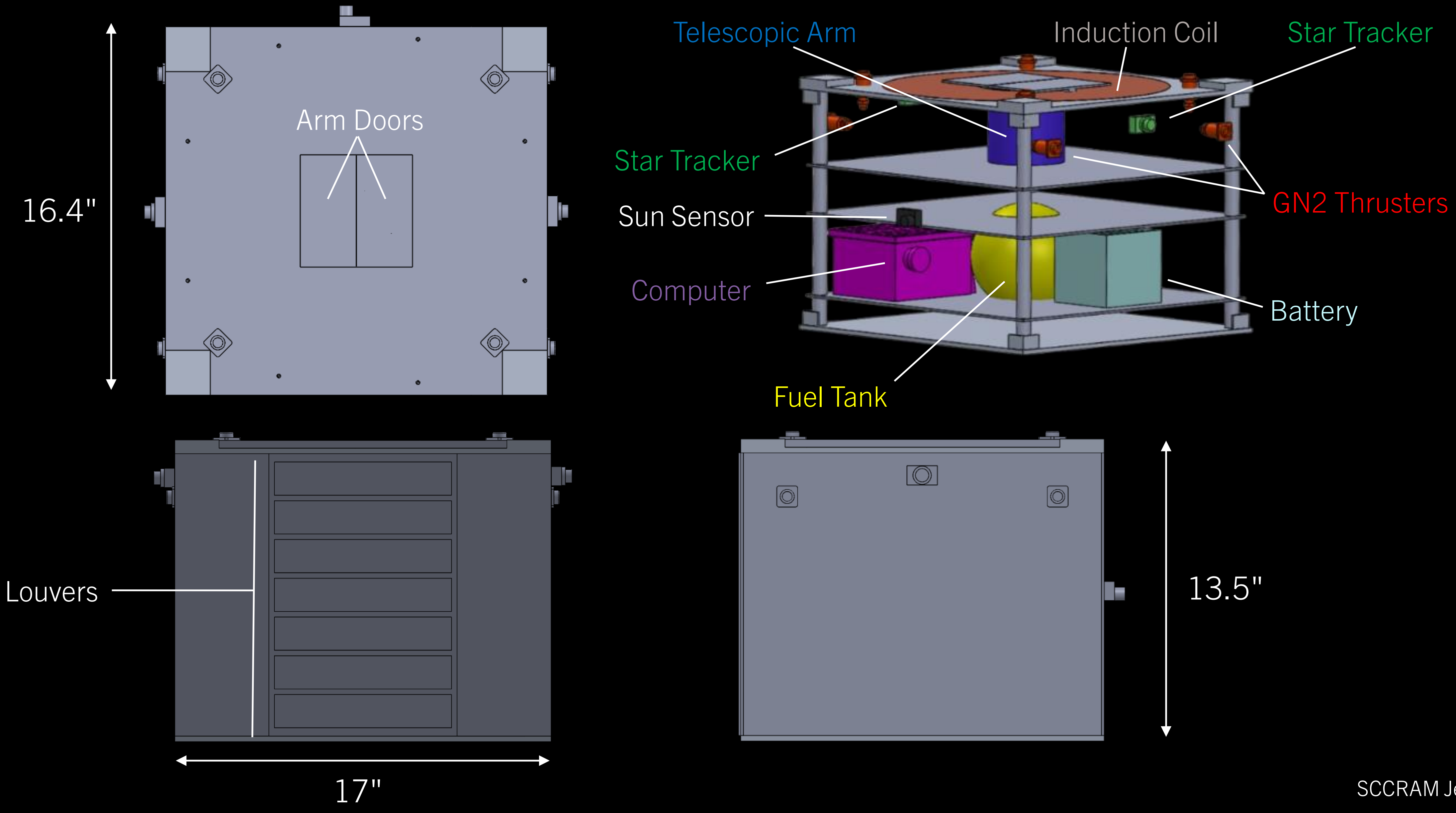
2.4 SYSTEMS ENGINEERING MILESTONES

Progression of Mission Development

Milestone	Date Completed
Program Manager Selection	September 13, 2024
Operations Definition	September 18, 2024
Top-Level Requirements	October 16, 2024
System Requirements Report	December 15, 2024
Conceptual Design Report	March 19, 2024
Trade Studies	January to March 2025
Path to PDR	March 2025

3-VIEW: CAD MODEL

Dimensioned and Labeled CAD Model

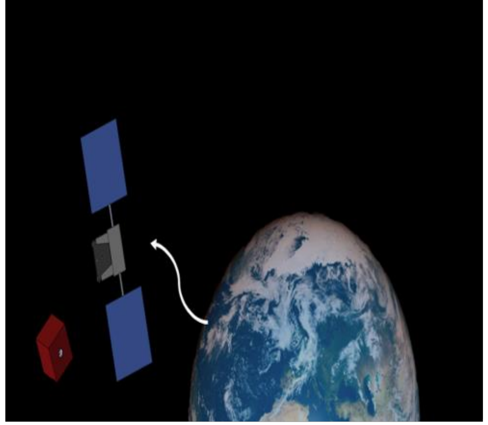


2.2 STORYBOARD OF COMPLETE OPERATION

COSMIC
CONSORTIUM FOR SPACE MOBILITY AND ISAM CAPABILITIES

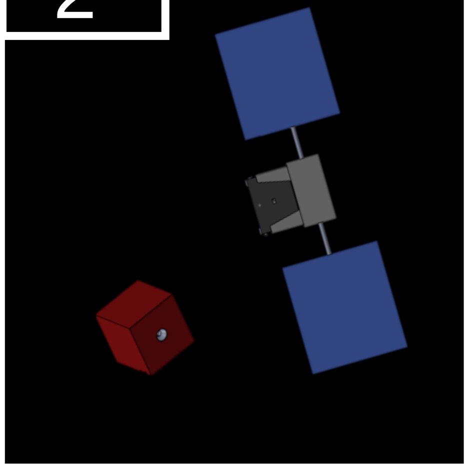
Concept of Operations

1



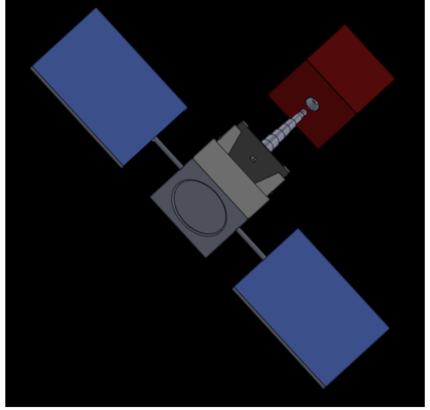
Rendezvous to the orbit of the target satellite

2



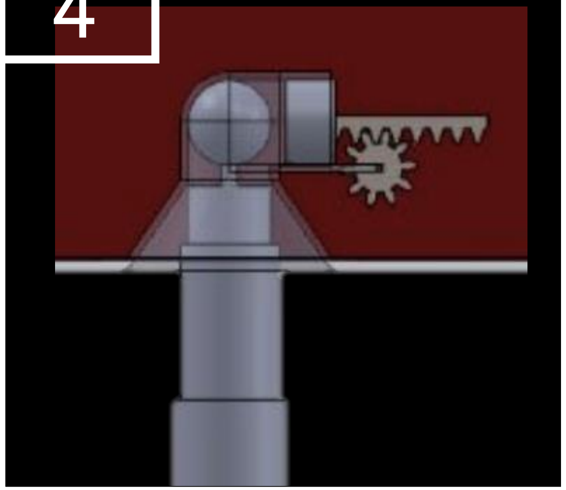
Align the faces and edges of the two satellites

3



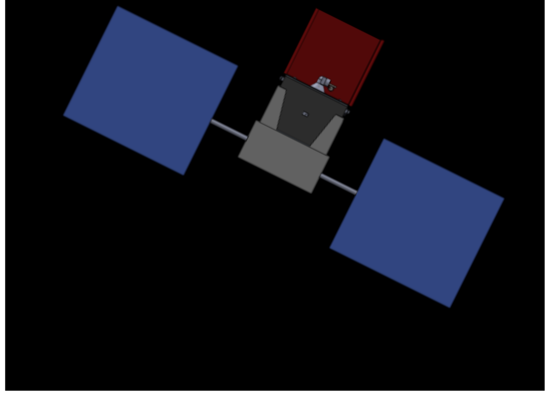
Extend telescopic arm and dock

4



Establish secure connection & retract arm

5



Begin power transfer via induction

Images by Coral Lee

2.1 ANIMATION OF KEY OPERATING SEQUENCE

SOLIDWORKS Animation

Launch

PAYLOAD SUBSYSTEM DESIGN

Thermal System Analysis

Key Features

- Multi-layer insulation
- Passive louvers

Payload Analysis

Characteristics	Louver System	Deployable Radiators
Complexity	Passive, operates with bimetallic springs which expand and contract based on the internal temperature of the payload wall, will be built directly as a part of payload	Passive, requires deployment, one of the payload faces will have to be a radiator
Reliability	Operate based on thermodynamic principles and entropy, could encounter issues with sudden temperature changes i.e eclipses	Max heat loss: 2.75 W at 90deg, will continue to dissipate heat at a constant level, can reduce internal temperatures by around 50 C with the proper rotation
Efficiency	Responds to the internal payload temperature, could have interference when inside bus	Can be actively rotated, changing the total amount of heat dissipation but requires a 135-degree rotation to achieve "full deployment", will continually radiate given amount based on sunlight exposure
Power Consumption	Will not require power, some heat WILL be absorbed into the bimetallic springs which will need to be accounted for to properly dissipate heat ->backup will be installed additionally	Requires power (around 2.5W) for deployment and panel rotation
Volume Budgeting	Will be attached directly the payload, must create internal space within the payload for the louvers to fit	Will fit on the payload externally, probably along the bottom of the payload to fit inside the bus
Mass Budgeting	Aim for around 8 kg/m^2, need space for multiple flaps to properly dissipate heat but will be a part of the payload itself	Extra pieces required in additon to the full mass of the payload, 0.5 kg per panel (4 panels needed to keep the center of mass stable) meaning that around 2 additional kgs on top of the full mass of the payload will be needed
Dissipation Properties	Dissipates heat directly through the louver flaps, could run into issues when conducting control volume analysis	Vent system can be pointed towards deep space to release heat, easily removing excess heat from the system
Results		

PAYLOAD SUBSYSTEM DESIGN

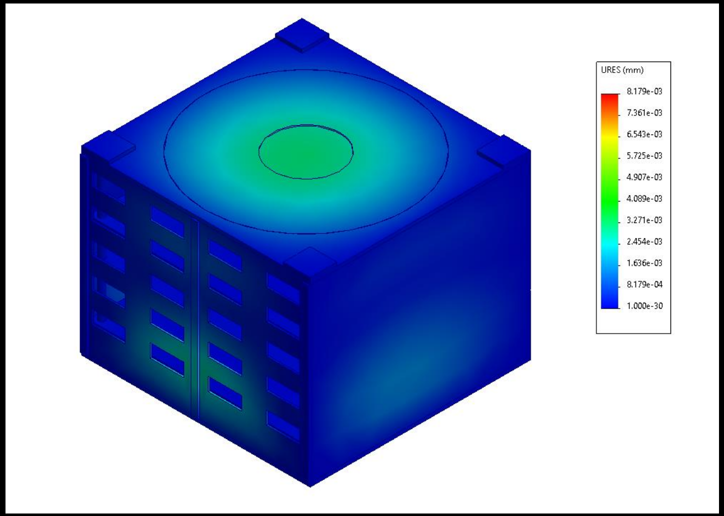
Structures System Analysis

CONSORTIUM FOR SPACE MOBILITY AND ISAM CAPABILITIES

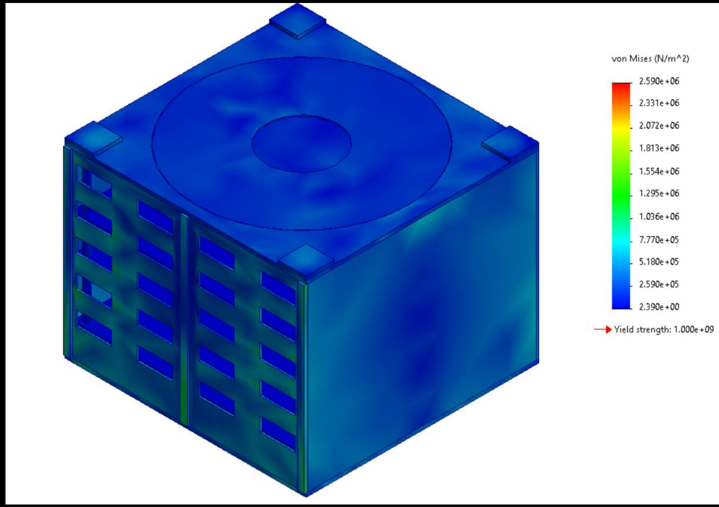
Key Features

- M60J carbon fiber frame
- Multiple “shelves” with CF rods
- Telescopic docking arm

Rank Percentage	Characteristics	Aluminum	Steel	Carbon Fiber
0.30	Performance: Ability to withstand forces and vibrations of launch and orbit.	2.00	3.00	3.00
0.10	Performance: Ability to thermally regulate the payload.	2.00	1.00	3.00
0.10	Performance: Ability to withstand radiation.	2.00	2.00	3.00
0.05	Performance: Ability to withstand the impact of micrometeorites and small space debris.	2.00	1.00	2.00
0.10	Performance: Ability to be drilled and shaped without complications.	3.00	2.00	1.00
0.30	Performance: Ability to be minimize overall structure weight.	2.00	1.00	3.00
0.05	Complexity: Ability to be located and purchased for manufacturing.	3.00	3.00	3.00
		2.15	**1.90**	**2.75**



Displacement (mm)



Von Mises Stress (MPa)

PAYLOAD SUBSYSTEM DESIGN

Power System Analysis

Key Features

- Lithium-ion battery
- 15” copper induction coil

PAYLOAD	
Propulsion	48.0000
Attitude Control	0.4300
Power	172.2000
Structure	0.0000
Thermal	5.0000
CDH	1.2000
Subtotal	226.8300

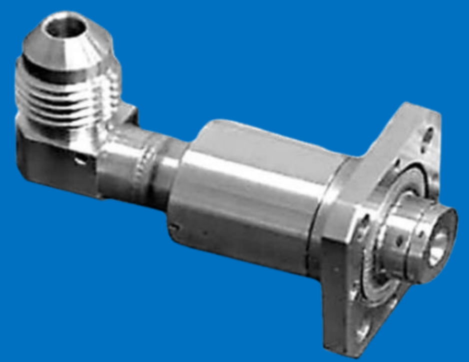
BUS	
Propulsion	0.1000
Power	22.2000
Structure	0.0000
Thermal	2.0000
Comms	5.8000
CDH	1.2000
Subtotal	31.3000

20% Margin	51.6260
TOTAL (Watts)	309.7560

PAYLOAD SUBSYSTEM DESIGN

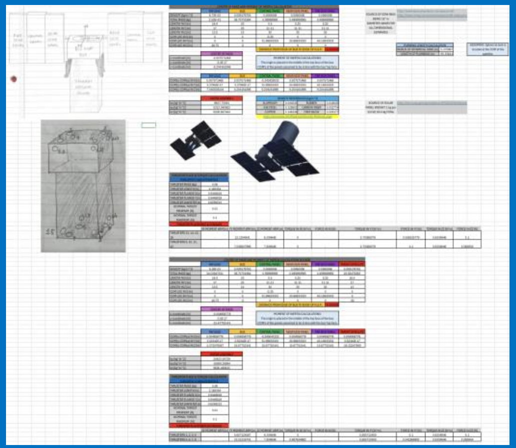
Propulsion System Analysis

1. THRUSTER SELECTION BY TRADE STUDY

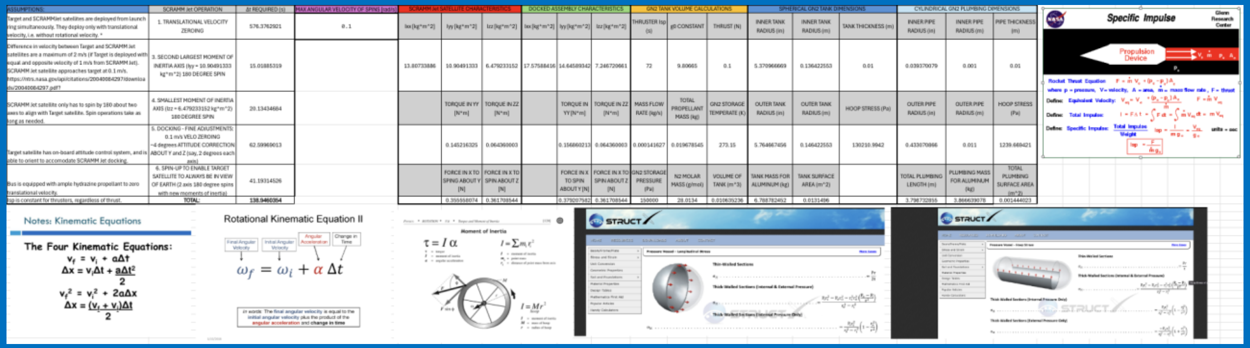


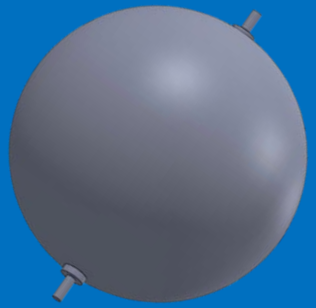
SVT01 Solenoid Valve GN2 Thruster

	ENGINE	MANUFACTURER	STATUS	ENGINE MASS (kg)	LENGTH (m)	PROPELLANT	NOMINAL THRUST (N)	SPECIFIC IMPULSE
COLD GAS	SVT01 Solenoid Valve Thruster	AMPAC	Flown on SNAP-1, DMC Alsat, UK	0.002231574	0	GN2	0	0.048689139
	Solenoid Actuated 58E142A Thruster	Moog	Flown on SIRTF/SPITZER	0	0.005048187	GN2	3.7415E-06	0
	Solenoid Actuated 58-118 Thruster	Moog	Flown on SAFER (Shuttle EVA)	0.000382555	0.00192749	GN2	0.000118708	0.057116105
MONOPROPELLANT	Liq AOCS thrusters	SEP	geos, exosat, ERS,	0.019382811	0.039926572	Hydrazine	0.000118708	0.647940075
	MONARC-5	AMPAC In-Space Propulsion	Flight qualified	0.030221882	0.083524553	Hydrazine	0.000152721	0.65917603
	MONARC-90	AMPAC In-Space Propulsion	Flight qualified	0.062739097	0.128040385	Hydrazine	0.003060885	0.666666667
	MONARC-445	AMPAC In-Space Propulsion	Flight qualified	0.100994644	0.178522258	Hydrazine	0.015135719	0.666666667
	MRE-0.1	Northrop Grumman	Chandra X-ray Observatory, DSP, STEP 4	0.030859475	0.070674621	Hydrazine	2.68708E-05	0.595505618
	MRE-1.0	Northrop Grumman	Pioneer, HEAO, TDRSS, FLTSATCOM, EOS, SSTI, STEP4	0.030859475	0.076640661	Hydrazine	0.000115306	0.602996255
	MRE-5.0	Northrop Grumman	GRO	0.09461872	0.111519045	Hydrazine	0.000952041	0.655430712
	MR-103G	Aerojet	Flight proven	0.020020403	0.069756769	Hydrazine	6.12245E-06	0.543071161
	MR-111C	Aerojet	Flight proven	0.020020403	0.067921065	Hydrazine	4.38776E-05	0.5917603
	MR-107N	Aerojet	Flight proven	0.046161693	0.088113814	Hydrazine	0.003707144	0.644194757
	CHT-1	EADS Astrium	>500 units flown	0.017470033	0.069297843	Hydrazine	1.05442E-05	0.535580524
	CHT-20	EADS Astrium	Flight proven	0.024164754	0.079853144	Hydrazine	0.000268367	0.625468165
BIPROPELLANT	Aestus	EADS Astrium	Ariane 5 upper stage	0.700331548	1	NTO/MMH	1	1
	S400-12 (-15)	EADS Astrium	>60 missions flown	0.228513134	0.221202386	NTO, MON-1, MON-3 and MMH	0.014285379	0.97752809
	10 N Bipropellant Thruster	EADS Astrium	>90 spacecraft have these thrusters	0.021295588	0.048187242	NTO, MON-1, MON-3 and MMH	0.000339796	0.876404494
	Unified Propulsion System - Apogee Kick Engine	Japan IHI company ltd	provides GEO insertion and attitude/orbit control for 2t-class satellites	1	0.463056448	NTO/Hydrazine	0.057822809	0.990262172
	R-40	Aerojet	Flight proven (Space Shuttle)	0.432542719	0.244607618	NTO (MON-3)/MMH	0.131632358	0.838951311
	HiPAT	Aerojet	Apogee thruster Flight Proven	0.330527927	0.278568151	NTO (MON-3)/MMH	0.015135719	0.985018727
	R-1E	Aerojet	Flight proven (Space Shuttle)	0.126498342	0.133547499	NTO (MON-3)/MMH	0.003775171	0.835205993
	5lb Cb	AMPAC In-Space Propulsion	Flight qualified	0.051262433	0.089490592	NTO/MMH	0.000747959	0.883895131
	LEROS LTT	AMPAC In-Space Propulsion	Flight qualified	0.037235399	0.114272602	NTO/MMH	0.000305782	0.812734082
	TR-308 Dual Mode Liquid Apogee Engine	Northrop Grumman	Flown on Chandra X-ray Observatory	0.302473859	0.314364387	NTO/N2H5	0.016054087	0.992509363



2. THRUSTER PLACEMENT ANALYSIS, THRUST & TORQUE OUTPUT





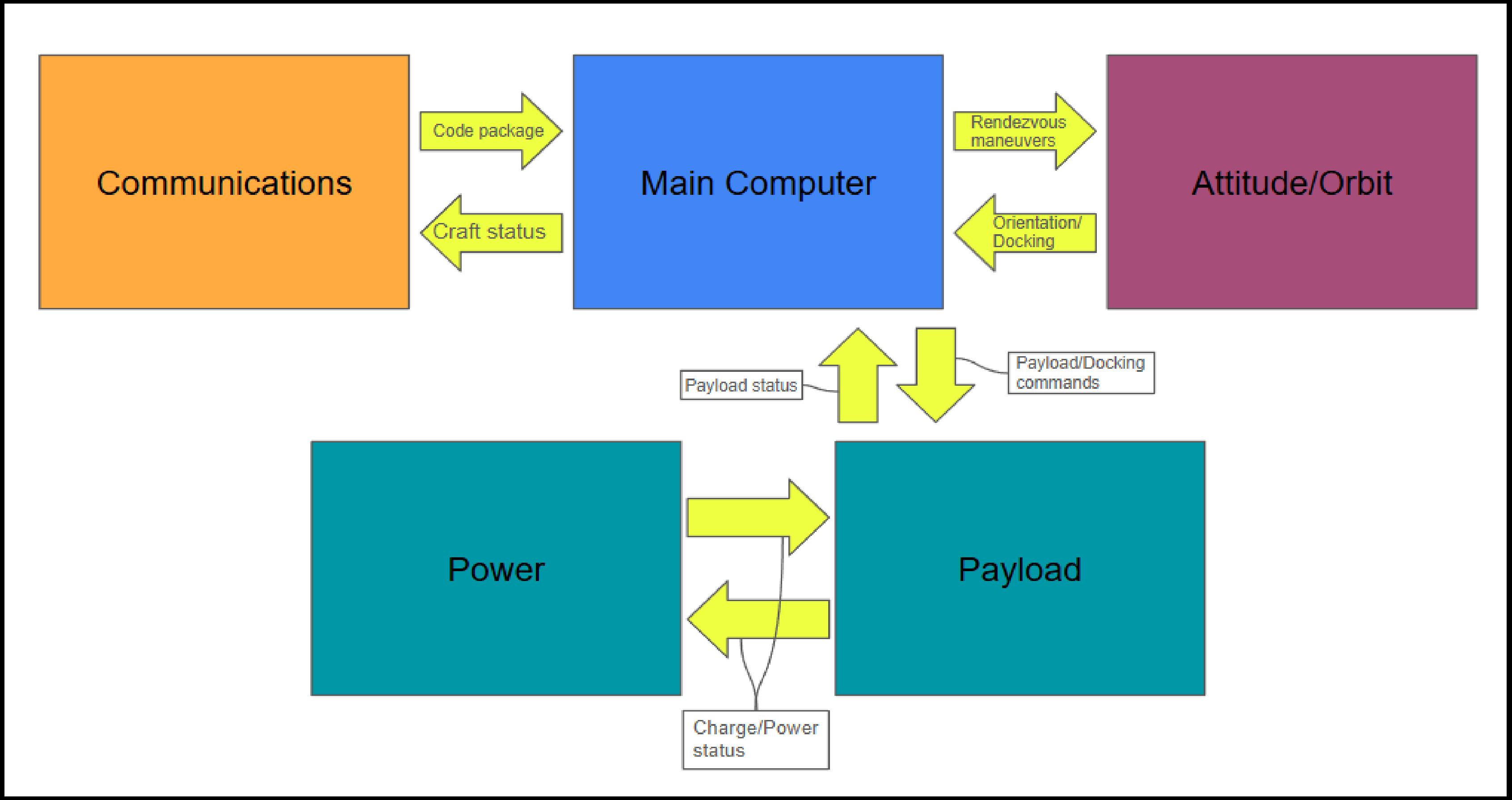
3. SPHERICAL GN2 TANK MASS & VOLUME CALCULATION

Thruster Image: Nammo (U.K.) Ltd., *Spacecraft Cold Gas Thruster Valve - 10mN to 100mN Thrust*, image from datasheet, Mar. 2021. Accessed: Apr. 10, 2025. [Online]. Available: https://www.nammo.com/wp-content/uploads/2021/03/2021-Nammo-Cheltenham-Spacecraft-Cold-Gas-Thruster-Valve.pdf

2.3 DATA HANDLING & COMMUNICATIONS

Command & Data Handling

Criterion	PC-104	Backplane
Size	Compact in size due to configuration standardization	Larger size to accommodate adaptable integration
Weight	Lightweight due to compact configuration	More weight due to larger configuration
Power Draw	Power distribution across individual components constrained due to small size configuration	Centralized power distribution across components
Signal Integrity	Constrained bandwidth and lower signal integrity	High bandwidth and better signal integrity
Expandability/ Flexibility	Stack height limitations and rigid modularity	Flexible configuration and able to be expanded due to larger configuration size
Cost	Lower component and configuration cost	Higher component and configuration cost
Complexity	Standardized and modular design	Higher complexity due to flexible configuration
Overall Performance	Limited in performance due to size, power, and bandwidth constraints	Increased performance based on power distribution, flexibility, and better signal integrity
Results	3	5



Graphic by Christian Bouarouy

MASS BUDGET

Expected Mass & Bill of Materials

PAYLOAD	
	Propulsion
	Holding thrusters (x8)
	Activaitng thrusters (x4)
	Gas N2 tank
	Plumbing
	Attitude Control
	Star trackers (x2)
	Sun sensor
	Power
	Induction coil
	Inverter (DC to AC)
	Rectifier (AC to DC)
	Secondary battery
	Wiring
	Structure
	Shell
	Levels (x4)
	Rods (x4)
	Screws (x8)
	Telescopic arm
	Thermal
	Louvers
	MLI covering
	Active Control Backup
	CDH
	On-board computer
	Wiring

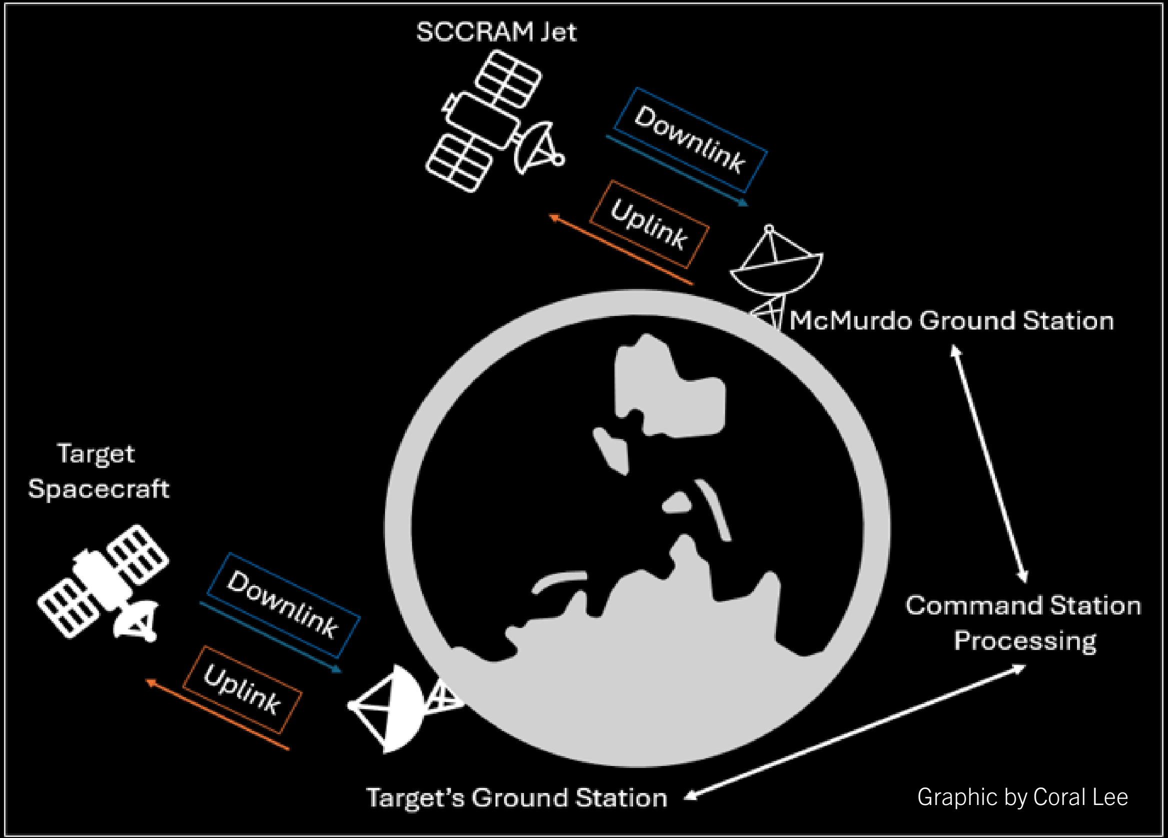
BUS	
	Propulsion
	Hydrazine thrusters
	Power
	Primary battery
	Structure
	Aluminum alloy structure
	Thermal
	Radiators (active)
	Comms
	Antenna
	Software designed radio
	CDH
	On-board computer

Propulsion	11.3951
Attitude Control	0.1090
Power	3.5563
Structure	7.9138
Thermal	1.2164
CDH	1.0100
20% Margin	5.0401
TOTAL (kg)	30.2407

2.3 DATA HANDLING & COMMUNICATIONS

Communication Architecture & Communication Concept of Operations

- Store & Forward: 1 pass every 90min available
- S-Band
- Pass 1: Downlink
  - Orbital information from SCCRAM Jet & Target Satellite
  - Power Status of Target Satellite
- Pass 2: Uplink
  - Orbital Transfer Commands
  - Docking Commands
  - Charging Commands
- Pass 3: Verification



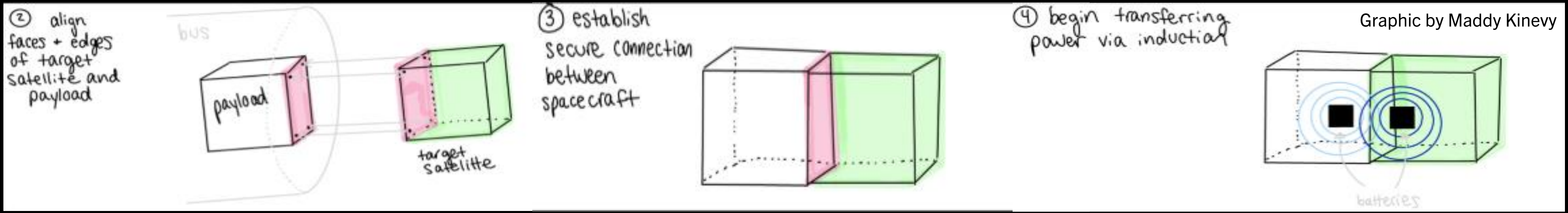
Quantitative

Download Data Rate	1.0 Mbps Average, 1.92 Mbps Max
Upload Data Rate	0.96 Mbps
Uplink Margin	37.43 dB
Downlink Margin	40.70 dB

3.1 INNOVATIVE CONCEPTS

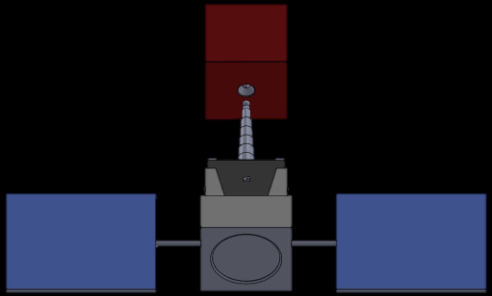
Top Three Innovations

- Induction Charging
  - Using principles of induction to wirelessly charge a target satellite from a close distance



Graphic by Maddy Kinevy

- Telescopic Arm and Probe Docking
  - Using a telescopic arm to safely dock with and make contact with the target satellite



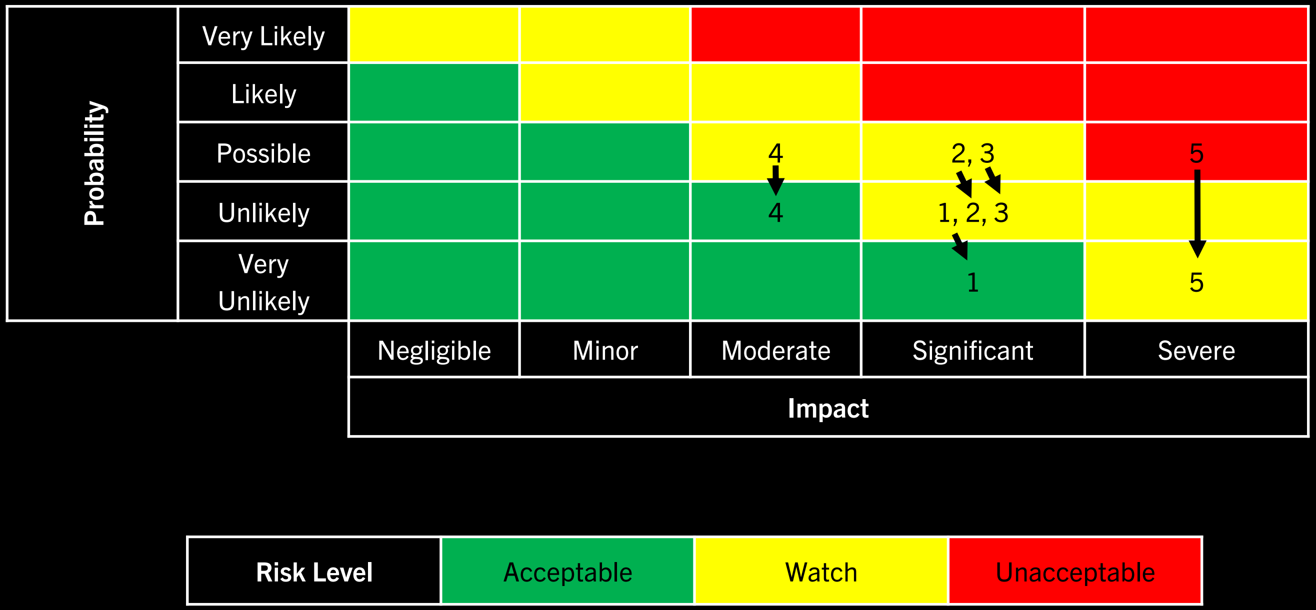
Graphic by Aidan McGrath

- Magnetic Docking
  - Using a series of magnets to dock face-to-face with the target satellite

1.5 RISKS

Risks to Mission Success

SCCRAM Jet Mission Risks		
	Risk	Mitigation Strategy
Docking	1. Docking arm connection	Propellant reserve for additional ΔV maneuvers.
Docking	2. Docking arm extension	Spin satellite to induce a radial acceleration of telescopic arm.
Power	3. Induction coil EM field	Ensure high magnetic permeability and shielding in the target satellite.
Power	4. Distance between coils	Explore using resonant inductive coupling.
Thermal	5. Eclipses and solar flares	Incorporate active control backup for louver system.



3.2 TECHNOLOGY GAP ASSESSMENT

Gaps in ISAM Technology

- Compact and low-weight electric propulsion
  - Offers very high specific impulse
  - Enables servicing of multiple satellites per SCRAMM Jet mission
- More power and energy dense batteries with higher discharge rates
  - Demand less docking time with SCRAMM Jet satellite
  - More efficient power transfer and discharge rate
- Nickel-Hydrogen battery that can withstand space environments
  - Better fit for mission
- Universal docking mechanisms for small satellites
  - Enable servicing of satellites regardless of origin or maker

3.3 BIGGEST CHALLENGES ENCOUNTERED

Hardest Issues to Solve

- Developing a feasible docking solution
  - Multiple iterations over the course of the year
- Developing a low-mass propulsion system with enough ΔV for attitude control & docking
  - Thorough research and analysis required for a suitable propulsion solution
- Initial payload requirements
  - Defining the purpose of the mission

4.1 PAPER

SCRAMM Jet White Pages Details

SCCRAM Jet Final Report Aspects	
Abstract Length	200 words
Paper Length	19 pages
Number of References	27

Publishing at AIAA SciTech Conference, January 12-16 2026 in Orlando, FL

LESSONS LEARNED

Key Knowledge Gained For Future Careers

- A thorough process is required to create a successful engineering design
  - In-depth analysis
  - Integrated research
- Collaboration between subsystems
  - Interwoven challenges
- Extracting pertinent information
  - Condense key points for team comprehension

1.6 PATH TO PDR

BCT X-Sat Bus Integration

BCT Venus Class X-Sat Bus – Subsystems Verification		
Components		Verification
STRUCT	Aluminum alloy 6061 frame	BCT Metal Procurement Standards; launch load analysis via SOLIDWORKS Simulation
POWER	Lithium-ion battery	BCT Venus Class X-Sat Bus datasheet; Ibeos B28 28-Volt Modular Battery datasheet; power budget analysis
POWER	Dual solar array	Cosmic Capstone Request for Proposal; BCT Venus Class X-Sat Bus datasheet
THERM	MLI Blankets, Deployable Radiator	Emissivity calculations; heritage systems
PROP	Additional thrusters	BCT X-Sat Venus Class Bus data sheet; torque equalization analysis
CDH	On-board computer	Analysis on backplane integration and component configuration for mission requirements
COMMS	Store & Forward; S-band	Link budget analysis

1.6 PATH TO PDR

Future Work

CONSORTIUM FOR SPACE MOBILITY AND ISAM CAPABILITIES

Future Work		
	SCCRAM Jet Payload	BCT X-Sat Venus Class Bus
STRUCT	Additional FEA analysis with all CAD internals	Research into in-orbit torque(s) on solar arrays
POWER	Improving coil efficiency, real-life power transfer verification	Confirmation of dual solar arrays and battery details
THERM	Thermal Analysis using CAD software	Thermal Analysis using CAD Software
PROP	ADCS Design, Docking Simulation	Confirmation of Thruster placement, ADCS Design, Docking Simulation
CDH	OpenC3 Cosmos application analysis	OpenC3 Cosmos application analysis

SUMMARY/CONCLUSION/HIGHLIGHTS

Summary of SCRAMM Jet Mission

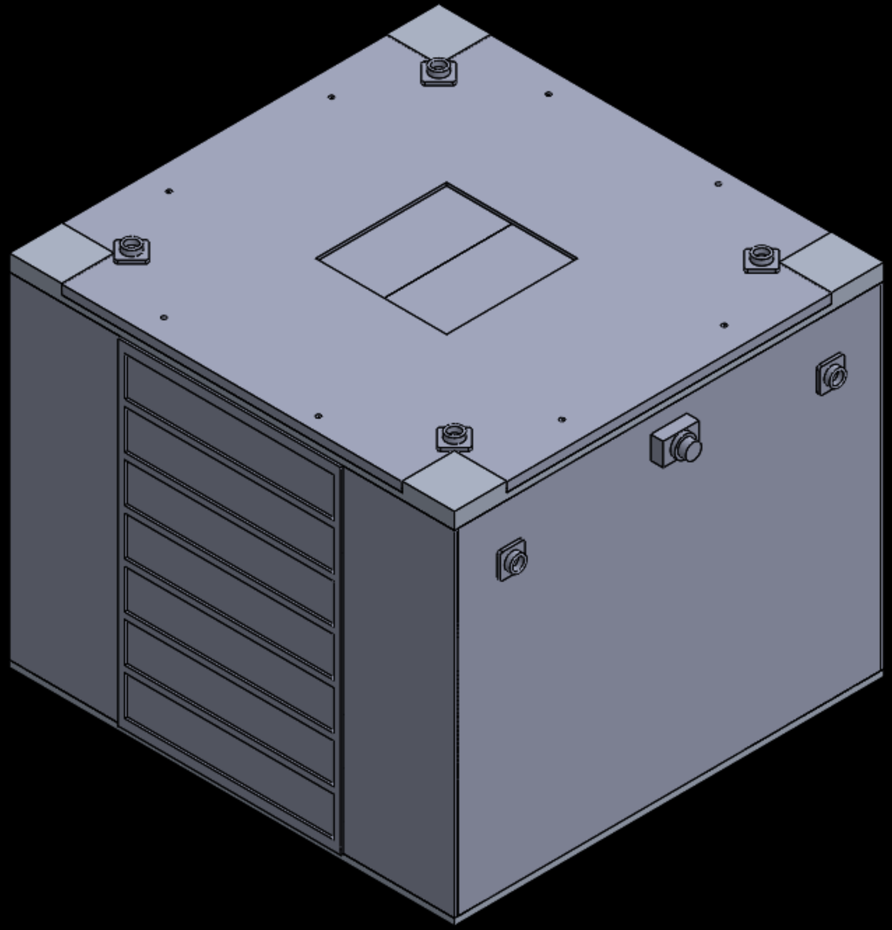
COSMIC
CONSORTIUM FOR SPACE MOBILITY AND ISAM CAPABILITIES

Key Takeaways

- Functioning satellites often decommission due to power depletion
- Close-contact induction charging offers a safe method of power resupply

Impacts to ISAM

- Increased servicing to decommissioned satellites
- Reducing space debris
- Saving money, resources, and labor



Questions?

POTENTIAL TARGET MISSION: LANDSAT NEXT

COSMIC
CONSORTIUM FOR SPACE MOBILITY AND ISAM CAPABILITIES

NASA's Landsat Next

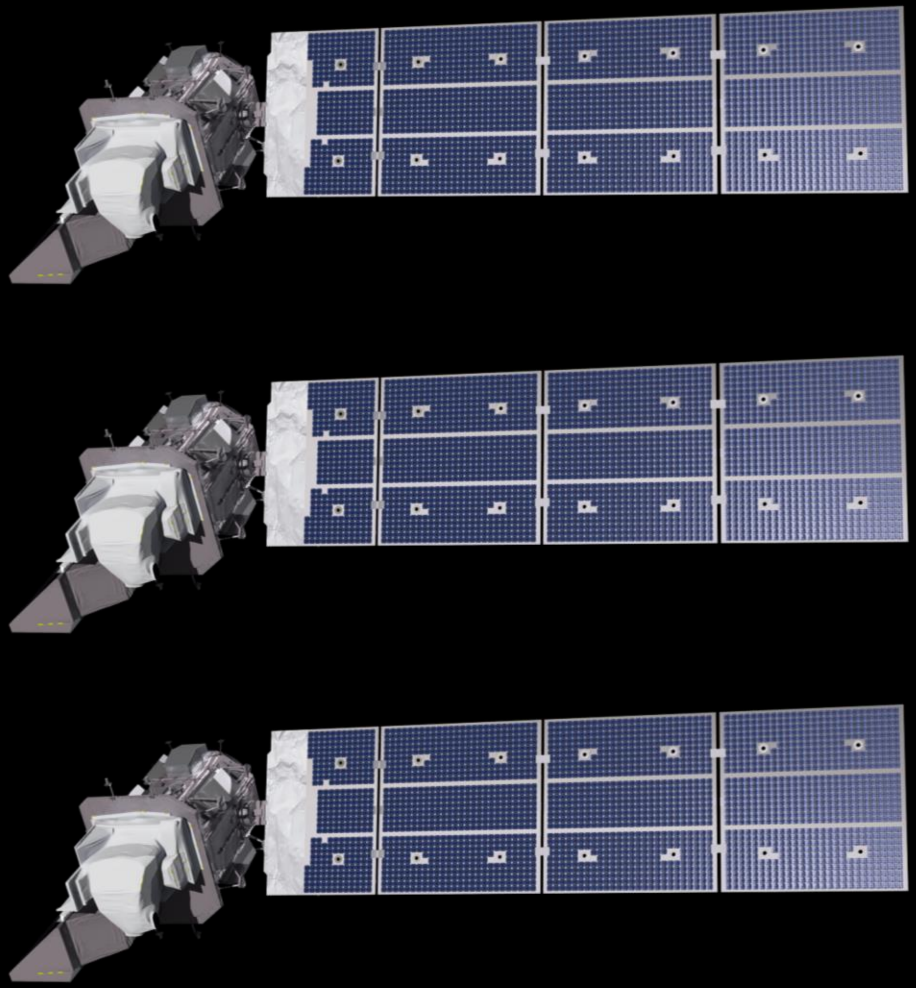
Purpose: Earth observation and monitoring

Expected Launch: 2031

Orbit: SSO at 653 km altitude

Status: Concept and technology development

Lifespan: 5 years, due to power depletion



Images: NASA, "NASA's Artemis I rocket completes first wet dress rehearsal," *NASA's Goddard Space Flight Center*. [Online]. Available: https://svs.gsfc.nasa.gov/13259. [Accessed: Apr. 6, 2025]

BACK UP SLIDES

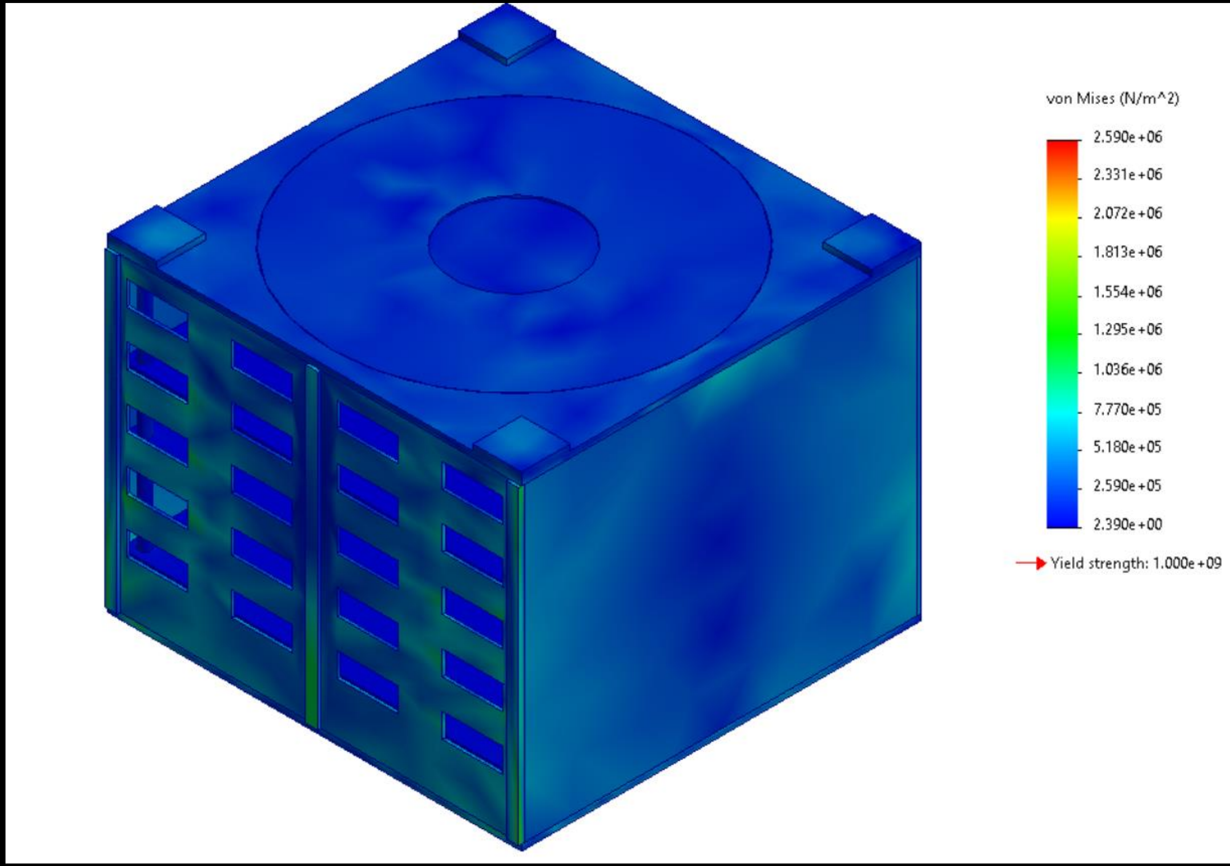
-CONCLUSION -> take away and impact

AUTONOMOUS COMMANDS

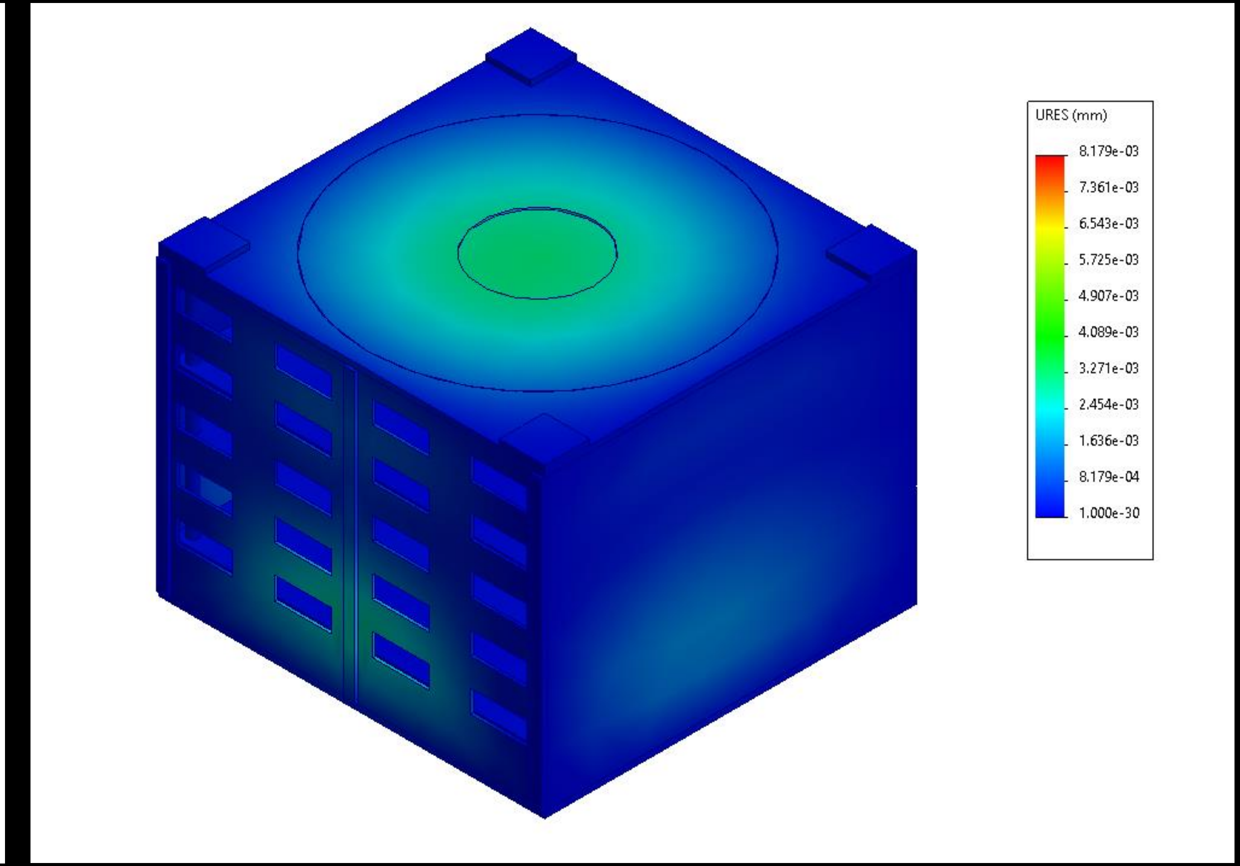
1. Attitude data is sent to ground.
2. Payload docking probe enters the target socket.
3. Target satellite socket fastens the probe.
4. Telescopic probe arm is retracted.
5. Inductive charging initiates.

FEA ANALYSIS

CONSORTIUM FOR SPACE MOBILITY AND ISAM CAPABILITIES



Von Mises Stress (MPa)

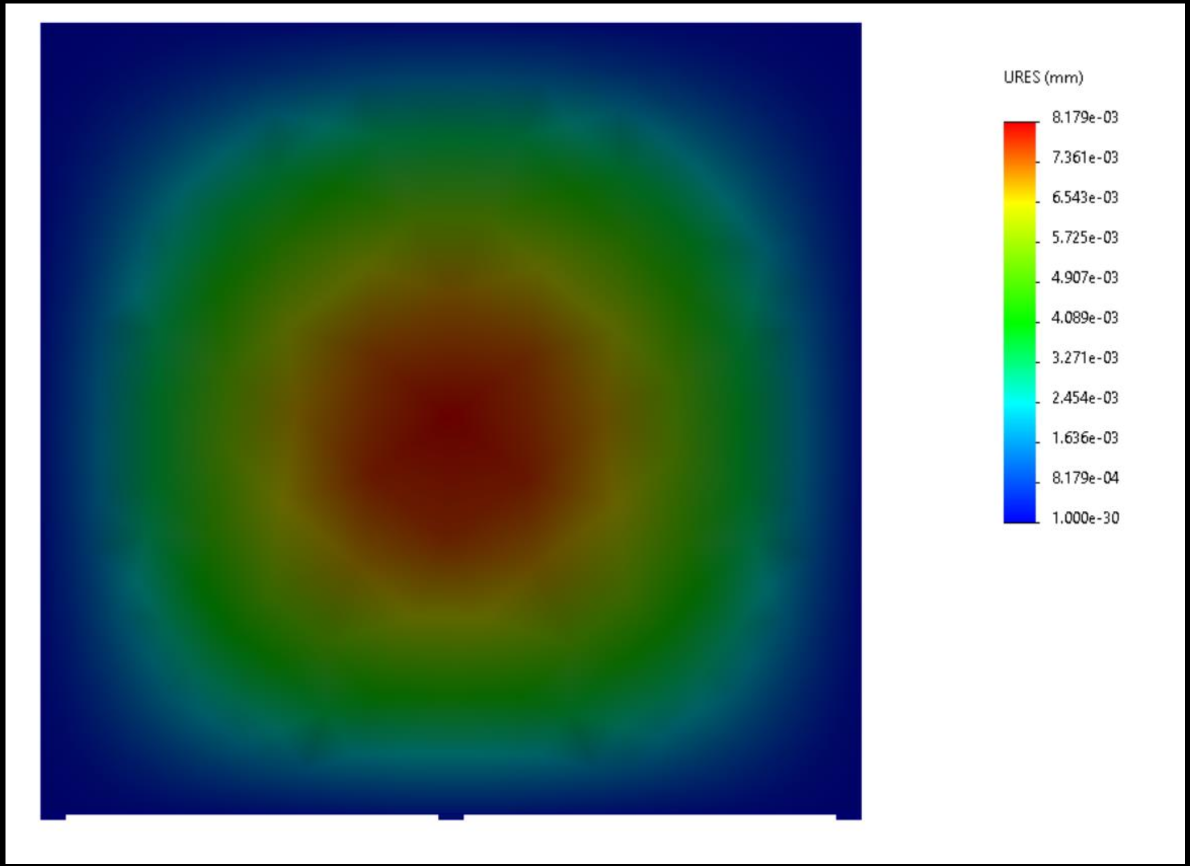


Displacement (mm)

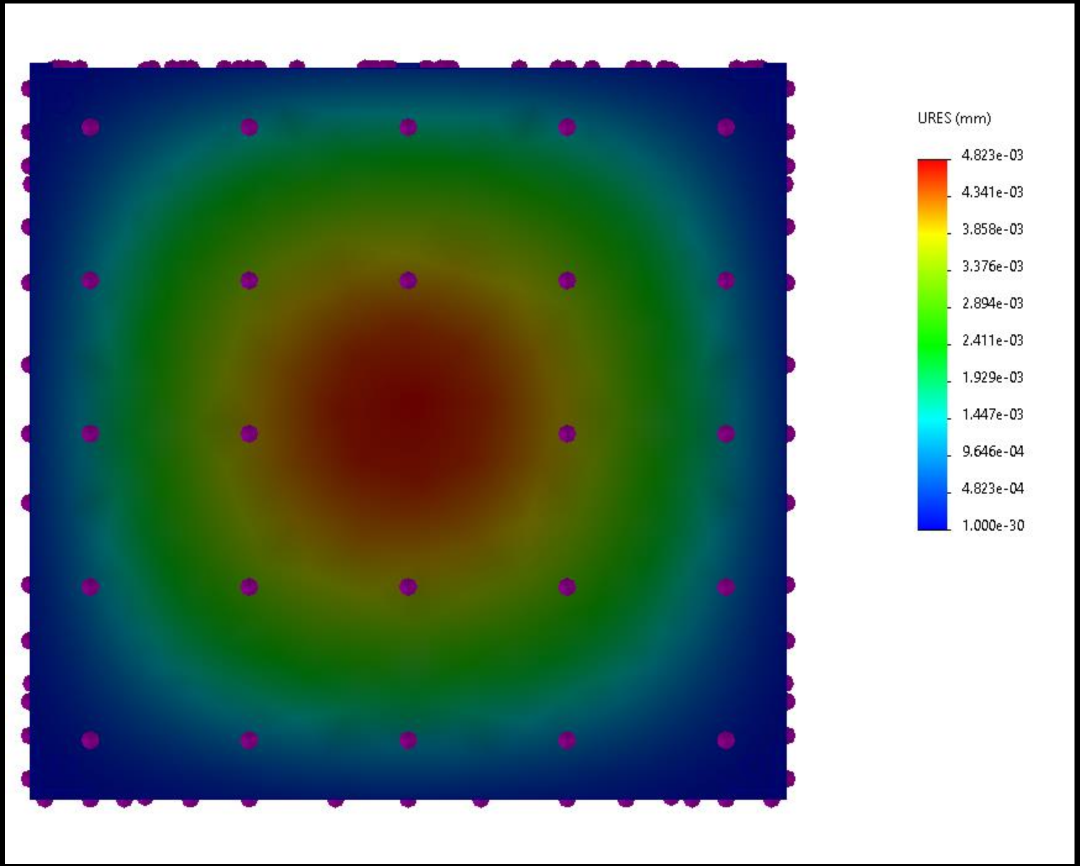
Images by Maddy Kinevy

FEA ANALYSIS

CONSORTIUM FOR SPACE MOBILITY AND ISAM CAPABILITIES



Original Base Plate



Thickened Base Plate

Images by Maddy Kinevy

INDUCTION COIL DESIGN

SCCRAM Jet Mission - Induction Coil	
Outer Diameter (in)	15
Inner Diameter (in)	4
Number of Turns	11
Length of Coil (in)	323.2
Wire Thickness (in)	0.1

INDUCTION CHARGING CALCULATIONS

CONSORTIUM FOR SPACE MOBILITY AND ISAM CAPABILITIES

$$L = \frac{0.5\pi N(d_o - d_i)}{1000}$$

$$R = \frac{\rho L}{A}$$

$$V = \sqrt{PR}$$

$$I = \frac{V}{R}$$

$$Q = It$$

N = number of coil turns
L = total length of coil wire
A = cross-sectional area of wire

d_i = inner diameter
d_o = outer diameter

R = resistance
ρ = resistivity
I = current
V = voltage
Q = battery capacitance
t = time

LAUNCH VEHICLE

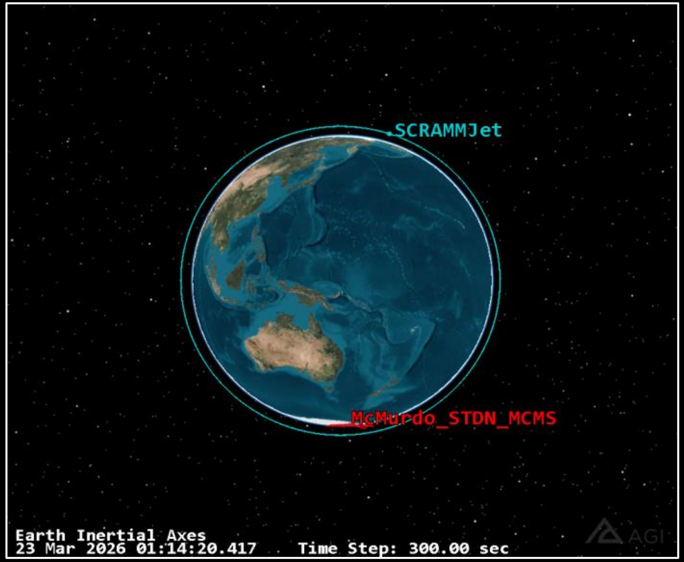
- Rocket Lab's Electron Rocket
- Capability to deliver a 200 kg payload to a 500 km altitude circular Sun-Synchronus Orbit (SSO) (Rocket Lab)
- Large fairing to support both SCRAMM Jet and demonstrative target satellite
- Launch would take place from Launch Complex 1 on New Zealand's Mahia Peninsula

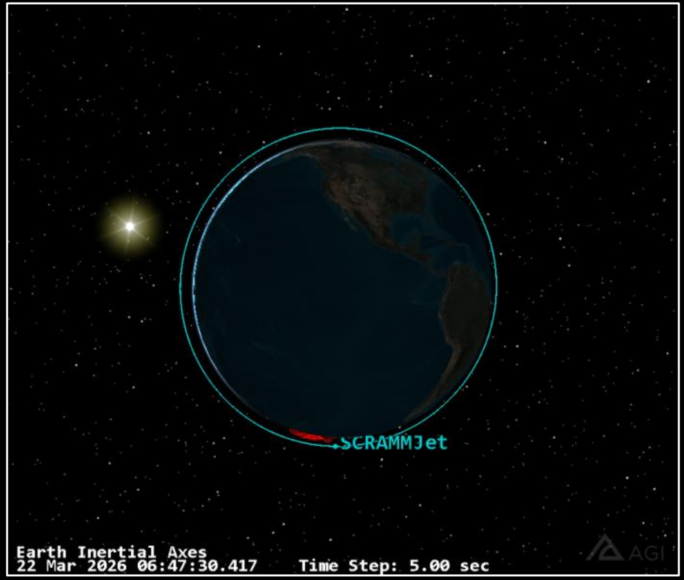
Rocket Lab, "Rocket Lab Successfully Launches 30th Electron Rocket & 150th Satellite to Space," Rocket Lab, Sep. 15, 2022. [Online]. Available: https://www.rocketlabusa.com/updates/rocket-lab-successfully-launches-30th-electron-rocket-and-150th-satellite-to-space/.

Rocket Lab. (2022). *Electron Payload User's Guide* (Version 7.0). Rocket Lab. Available at: https://www.rocketlabusa.com/assets/Electron-Payload-User-Guide-7.0-v6.pdf

ORBITAL ANALYSIS

- Orbit is a <u>500 km altitude SSO </u>(per Electron launch)
  - Constant solar flux
  - Only 1 ground station
  - A common orbit for Earth observation missions
- Must be during an equinox – most frequent ground station contact for SSO

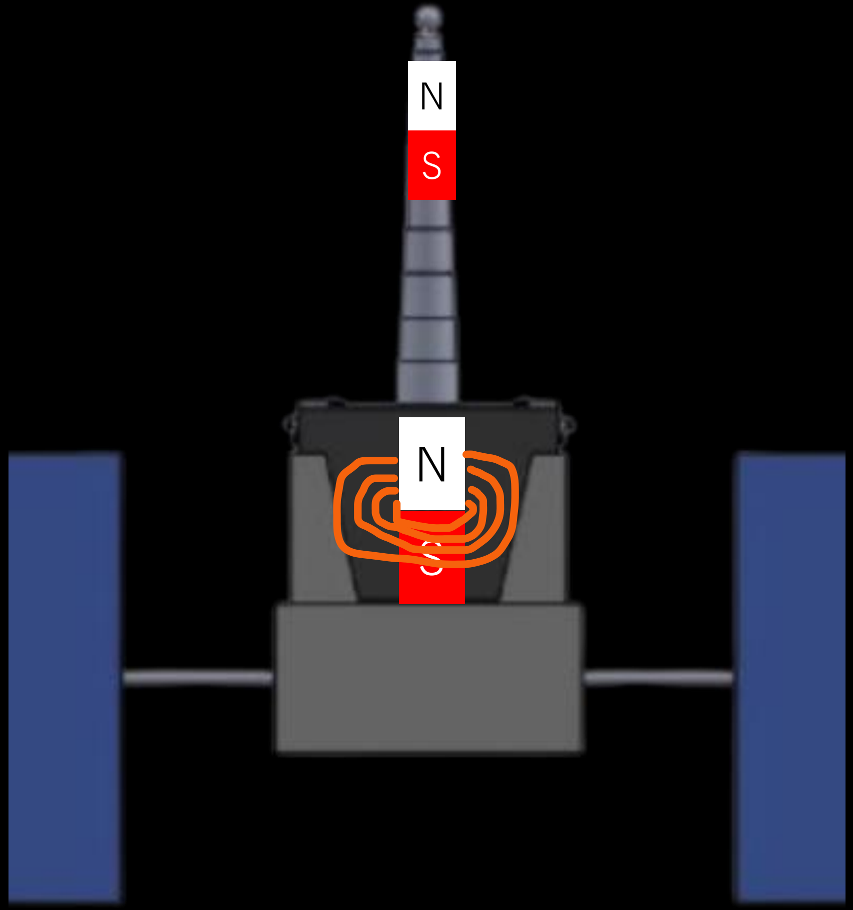




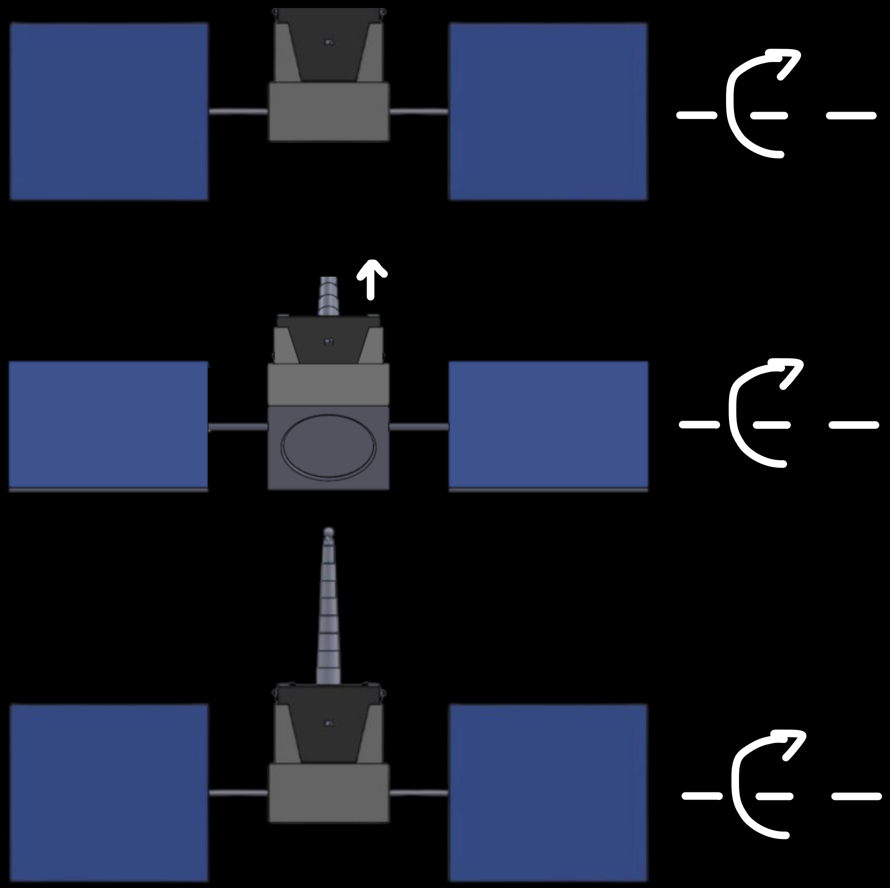
Images from STK Analysis by Aidan McGrath

TELESCOPIC ARM EXTENSION

"Solenoid" extension:



Spinning extension:



GROUND STATION-MCMURDO

- Located in the Arctic, conducive to polar orbit
- Owned by National Science Foundation
- S & X-Band capabilities
- 10 meter diameter
- 150 meter altitude
- 200 Watts

Comberiate, M. (1993). 3-Panel Picture of McMurdo Ground Station [Photograph]. https://amrc.ssec.wisc.edu/meetings/MGS/history.html

THERMAL TRADE STUDY FOR BUS

Bus Analysis		
Characteristics	Louvers (FFTC)	Deployable Radiators
Complexity	Passive, operates with bimetallic springs which expand and contract based on the internal temperature of the bus, will be built directly as a part of bus. Since the bus is small, an entirely different model of louver would have to be adopted to properly dissipate excess heat	Passive, requires deployment, one of the bus faces will have to be a radiator
Reliability	Operate based on thermodynamic principles and entropy, could encounter issues with sudden temperature changes i.e eclipses	Max heat loss: 2.75 W at 90deg, will continue to dissipate heat at a constant level, can reduce internal temperatures by around 50 C with the proper rotation
Efficiency	Responds to the internal payload temperature, could have interference when inside bus	Can be actively rotated, changing the total amount of heat dissipation but requires a 135 degree rotation to achieve "full deployment", will continually radiate given amount based on sunlight exposure
Power Consumption	Will not require power in principle, some heat WILL be absorbed into the bimetallic springs which will need to be accounted for to properly dissipate heat	Requires power for deployment and panel rotation
Volume Budgeting	Less space will be able to be used for the louvers (bus is small) which will lead to less emittance	As the bus is smaller, the deployable radiators would have to sit along the outside, being attached as one wall of the bus
Mass Budgeting	With the bus a lot smaller, smaller louvers would need to be used, meaning less mass would be a positive.	The deployable radiators will still be more massive as each panel holds a decent amount of mass, with 4 total panels the mass of the deployable radiators will exceed that of the louvers.
Dissipation Properties	Dissipates heat directly through the louver flaps, could run into issues when conducting control volume analysis	Vent system can be pointed towards deep space to release heat, easily removing excess heat from the system
Results		

POWER TRADE STUDY FOR BUS

Battery Characteristics

Characteristics	Lithium-Ion	Nickel-Cadmium	Nickel-hydrogen	Silver-Zinc
DOD	80-95%	80%	35-40%	80%
Discharge Rate (A/in^2)	0.1-1	0.1-0.5	0.1-0.5	0.13-0.21
Ability to Deep Discharge	Yes	Yes	Yes	Yes
Over Discharging Potential	significant	relatively low	very low	relatively low
Discharge Temp (deg F)	-4 to 140	-4 to 149	32-113	-4 to 140
Discharge Safety	safe	safe	safe	safe
Charge Rate	0.2C-1C	C/10	C/10	0.2C-4C
Over Charging Potential	low	relatively high	realtively low	high
Charge Temp (deg F)	32-113	32-113	50-86	-4 to 141
Charge Safety	safe	safe	safe	safe
Time Necessary to Charge	1 to 4 hrs	66 mins	12 to 14 hrs	6 to 8 hrs
Voltage Necessary to Charge (V/cell)	4.2	1.55	1.25	1.6
Nominal Voltage (V/cell)	3.7	1.2	1.25	1.65
Capacity (Ah)	50 to 10,000	1 to several 100	10 to 50	4.4 to 40
Energy Efficiency	80%	70-80%	85%	80-90%
Energy Density (Wh/kg)	150-300	50-80	140	100-150
Specific Energy Density (Wh/kg)	150-250	20-40	140	100-150
Power Density (W/kg)	250-700	150	220	100-600
Specific Energy (Wh/kg)	150-250	40-60	55-60	100-150
Cycle Life (years)	5	4	30	2
Degredation Rate (cycles)	2,000	400-1000	30,000	150-300
Service Life (years)	2 to 3	5 to 10	30	2-2.5
Operating Life (years)	5 to 10	8 to 25	30	1
Thermal Stability	No	Yes	Yes	Yes
Operating Temp Range (deg F)	59-95	-4 to 158	-4 to 158	131
Maintenance Requirements	very few	very few	very few	a few
Internal resistance (Ohms)	0.01-0.05	0.155	0.05	10
Vibration Resistance	low	high	high	moderate
Radiation Tolerance	limited	limited	good	No info
Leakage Potential	low	moderate-high	low	moderate
Total Numerical Trade Study Score	58	65	45	64