COSMIC

THE POWER OF COLLABORATION

COSMIC Capstone Challenge: Final Briefing

Team Prometheus
The Pennsylvania State University

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Advisor: Dr. Sara Lego
Mentor: Michael Hernandez

4/16/2025

Executive Summary

Semi-Autonomous In-Space Welding

- Need for in-space autonomous laser-cutting and welding

- Objectives
  1. **Rendezvous with a target piece of space debris**
  2. **Autonomous laser cutting in space**
  3. **Autonomous welding in space**

- Demonstrate autonomous welding, laser-cutting, and robotic grabbing technologies in LEO for future satellite servicing and assembly

- Current Status
  - Critical Design Review Complete
  - Integration with Venus X Class Bus
  - Working towards Preliminary Design Review

Team

Penn State

Vraj Patel

Yasmine Kadire

Michael Hernandez

Dylan Nastanski

Katie Blyler

Bryce Pochron

Joe Messner

2.4 Systems Engineering Milestones

Timeline for Functional Architecture completion, System Readiness Review, and CDR

- **September 14** – Selected Team Manager
- **October 7** – Project Scoping & Functional Architecture
- **December 15** – Defined System Requirements
- **February 18** – Completed Trade Studies
- **March 1** – Finalized Concept Design
- **March 19** – Began developing Path to PDR

4.1 Paper

Technical Report Information

- Highlighting key sections
  - Capability gap
  - Top level mission requirement
  - Mission overview
  - Power and Mass budget
  - Payload design
  - Host spacecraft integration
  - Risk and fault recovery options

- Key Components of the Paper
  - Abstract length: 175 words
  - Length of paper: 18 pages
  - Number of references included: 34
  - Potential places to publish: SciTech

Prometheus Payload

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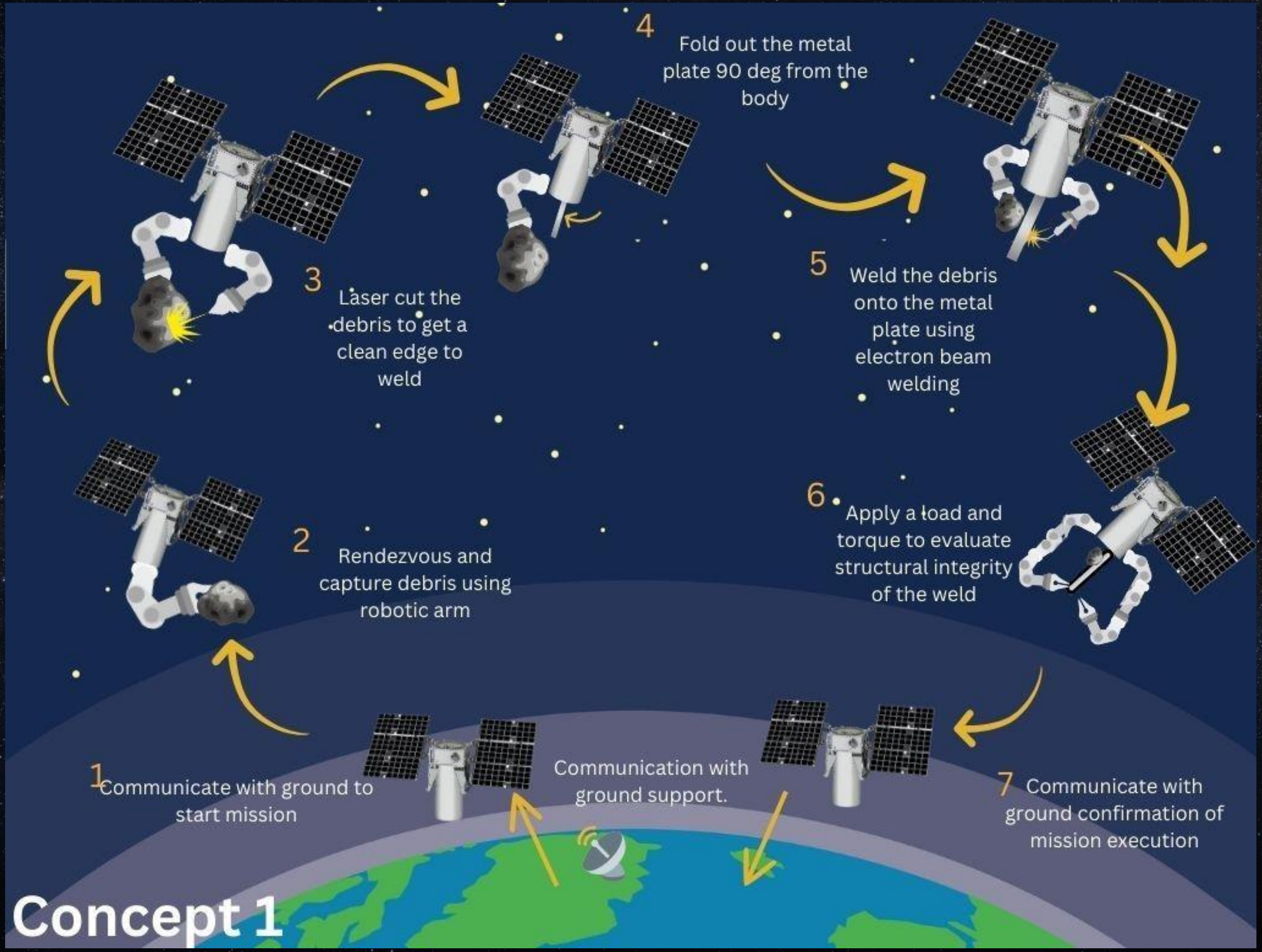
The Prometheus mission demonstrates an in-space servicing, assembly, and manufacturing (ISAM) payload capable of semi-autonomous rendezvous and debris capture, laser-cutting, and welding, integrated with the VENUS X-Class Bus. Using robotic arms equipped with a modified Paton electron beam welder and a conceptual fiber laser cutter, the system demonstrates procedures necessary for structural repairs and material processing in orbit. Diverse types of analysis confirm feasibility: Finite Element Analysis validated structural integrity under 5g launch loads and a power budget was designed through MATLAB's eclipse simulations and SMAD principles to ensure mission operations within the 444W cap from the Bus. Trade studies were used in the selection of actuators, computers, the welding gun, the laser-cutter, and the robotic arms. The mission advances through five stages including orbit determination, semi-autonomous rendezvous and capture of debris, semi-autonomous precision laser-cutting, semi-autonomous welding, and a brief structural test for weld integrity and then concludes its mission and deorbits. By demonstrating scalable in-space repair workflows, Prometheus advances the technological readiness of ISAM tools critical to future orbital infrastructure and debris mitigation efforts.

[1] Student, Aerospace Engineering, AIAA Undergraduate Student Member
[2] Associate Teaching Professor, Aerospace Engineering
[3] Senior GNC Engineer: Space Systems Architect

2.2 Storyboard of Complete Operation

CONOPS

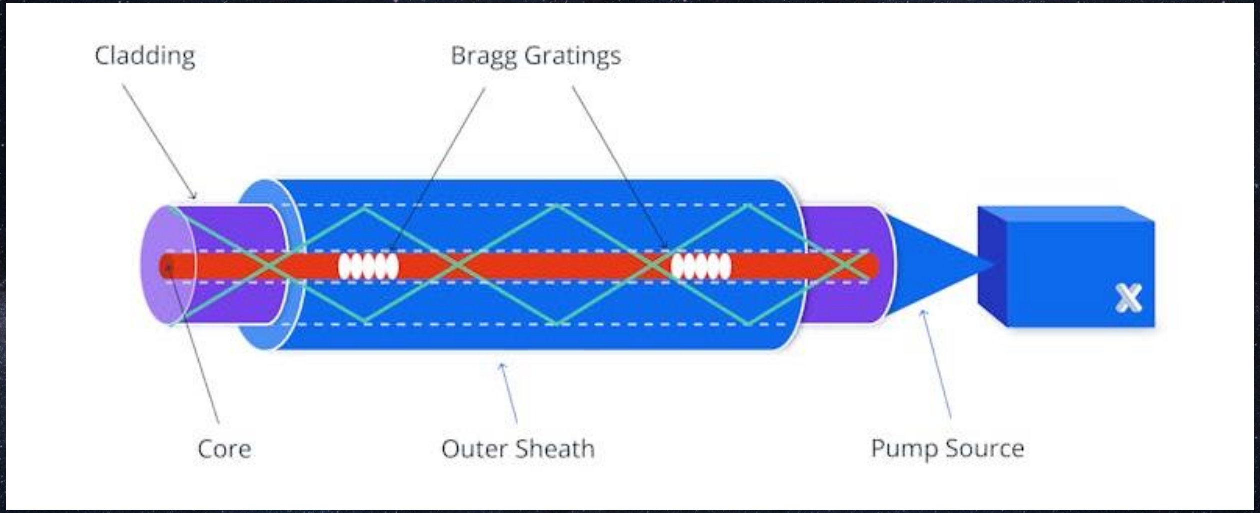
Orbit Determination
↓
Launch and Rendezvous (1)
↓
Laser Cutting (2)
↓
Welding (3)
↓
Testing & Shutdown



Laser Cutting

Ytterbium Doped Fiber Laser Cutting

- Laser diodes produce pump light, which is directed into the fiber. Ytterbium ions in the doped fiber absorb the light and get excited.
- Excited ions release photons as they return to lower energy states. Stimulated emission causes a chain reaction, amplifying the light.
- Bragg gratings trap and reflect light to build up the laser beam. Some light is let out, forming the output laser beam.
- A lens focuses the beam for precise cutting with minimal heat spread.



Electron Beam Welder Design

Paton's New Electron Beam Emission Gun

- Lanthanum Hexaboride cathode and triode emission system to generate an electron beam
- Aluminum Oxide insulation offers thermal radiation management and resistance to voltage breakdown
- Capable of welding aluminum alloys up to 6 mm thick and titanium or stainless steel up to 4 mm thick.
  - Specific power density reaches up to 16 kW/mm² in the focal zone.
- Weighs only 1.8 kg, making it suitable for robotic or manual operation in space environments.

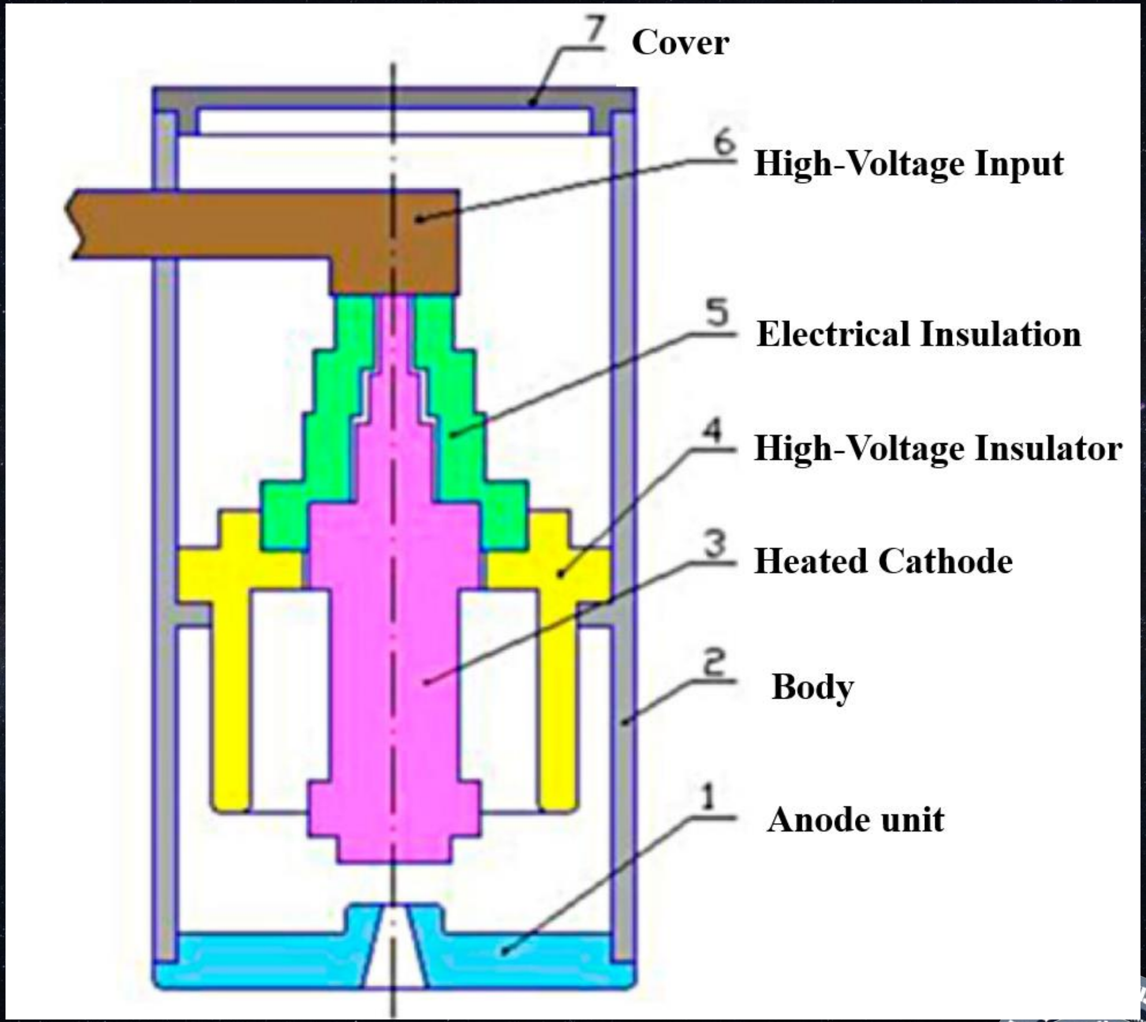
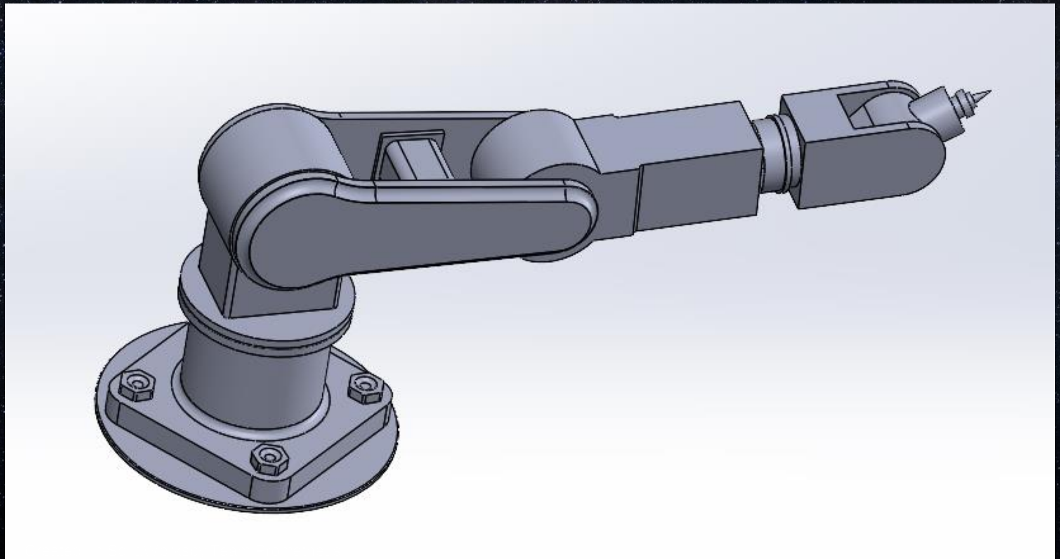


Image from Paton et. Al. , "New Electron Beam Gun for Welding in Space," ," *Science and Technology of Welding and Joining*, Vol. 24, No. 4, 2019, pp. 320–326. https://doi.org/10.1080/13621718.2018.1534794

Robotic Arm

Trade Study and Analysis

- Trade Study
  - Known and tested for in-space operations
    - High TRL Arms
- Hybrid Arm Design



Criteria	Weight	Canadarm2	Dextre	GITAI S1	MDA LMA	Maxar SPIDER	Luna Arm
Mass	10%	2	2	4	4	3	5
Power	10%	2	2	4	4	3	5
Payload Capacity	15%	5	4	3	4	5	2
Range of Motion	15%	4	5	3	4	4	3
Radiation/ Environment Tolerance	10%	5	5	3	4	5	4
Autonomy/ Control Modes	15%	3	4	5	4	5	4
Flight Heritage	10%	5	5	3	3	3	2
Cost & Availability	15%	2	2	5	4	3	5
Total Score	100%	3.4	3.6	3.9	**4.05**	3.85	4

1 = Poor | 3 = Moderate | 5 = Excellent

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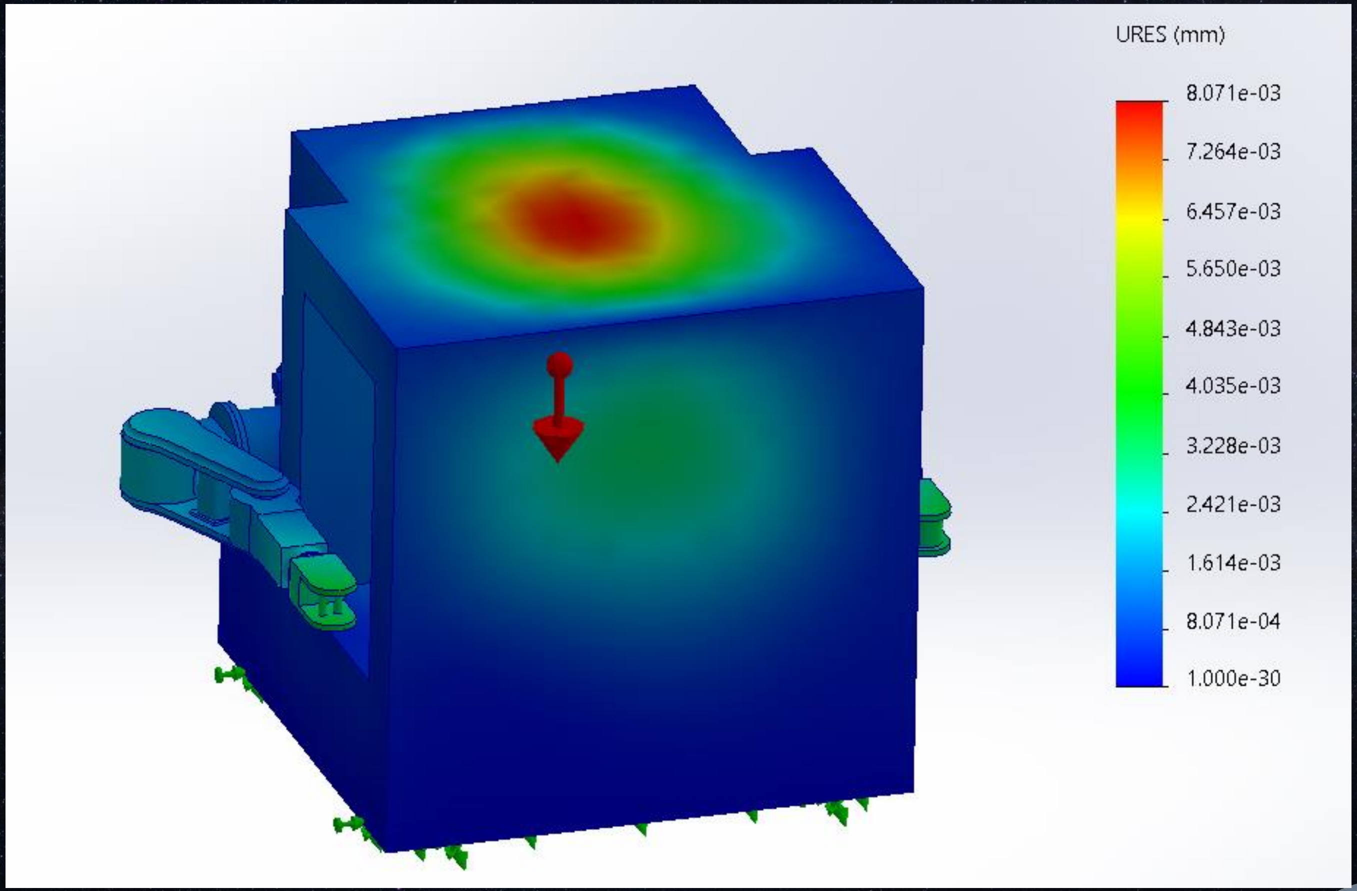
Structures

FEA of Payload experiencing Launch Conditions

- Using SolidWorks Simulation
- Simulating launch Conditions of 5g’s for Falcon 9
- Low deformations on the scale of µm
- Structures will not fail through the mission



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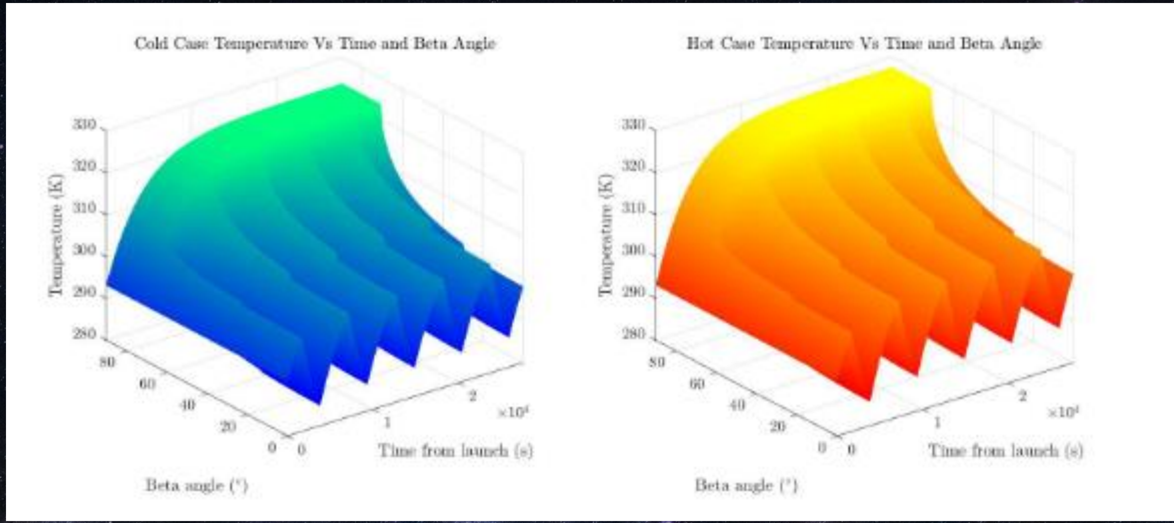
Thermal

Trade Study and Analysis

- Thermal equations
- Hot and Cold Cases
- Passive & Active Controls Systems
  - Potential Coating Material
  - Active Control Options



Versteeg, C., and Cotten, D. L., *Preliminary thermal analysis of small satellites* Available: https://s3vi.ndc.nasa.gov/ssri-kb/static/resources/Preliminary_Thermal_Analysis_of_Small_Satellites.pdf.

$$\dot{Q} = \dot{Q_{in}} - \dot{Q_{rad}} = q_{IR}A_{IR} + (1+a)q_{\odot}A_{\odot}\hat{s}\alpha + \dot{Q_{gen}} - A_s\sigma\varepsilon T^4$$

$$\dot{Q} = c_p m \frac{dT}{dt} \approx c_p m \frac{\Delta T}{\Delta t}$$

$$T_{i+1} = T_i + \frac{\Delta t}{c_p m}\dot{Q}_i$$

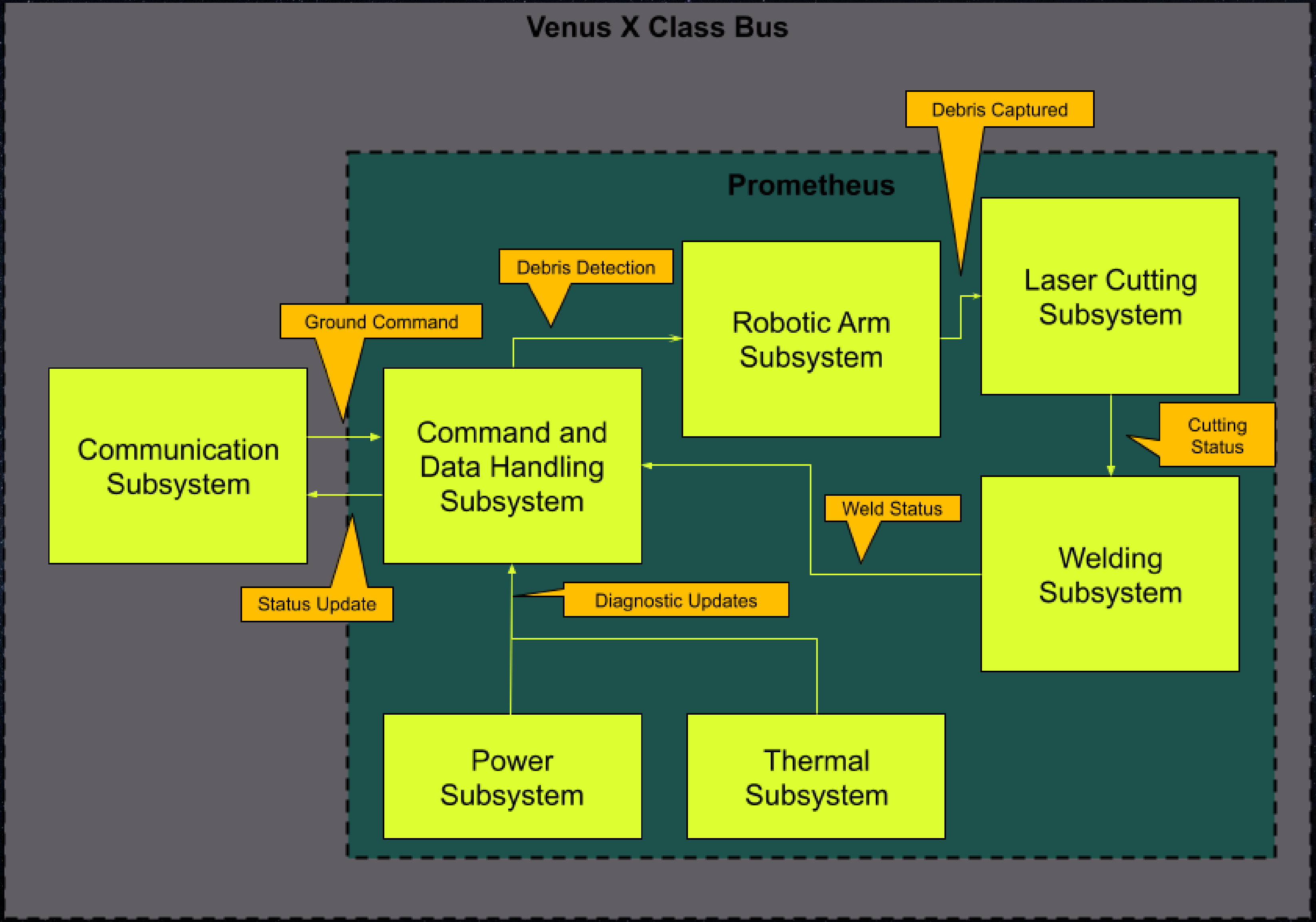
Versteeg, C., and Cotten, D. L., *Preliminary thermal analysis of small satellites* Available: https://s3vi.ndc.nasa.gov/ssri-kb/static/resources/Preliminary_Thermal_Analysis_of_Small_Satellites.pdf.

	Aeroglaze Z306	Carbon NS-7	N-150-1	Beryllium Copper	Hughson L-300	384 ESH* UV
Absorption	0.96	0.96	0.94	0.92	0.95	0.97
Emissivity	0.91	0.88	0.94	0.72	0.84	0.75

NASA Available: https://ntrs.nasa.gov/api/citations/19840015630/downloads/19840015630.pdf.

2.3 Data Handling and Comms

Data Flowchart

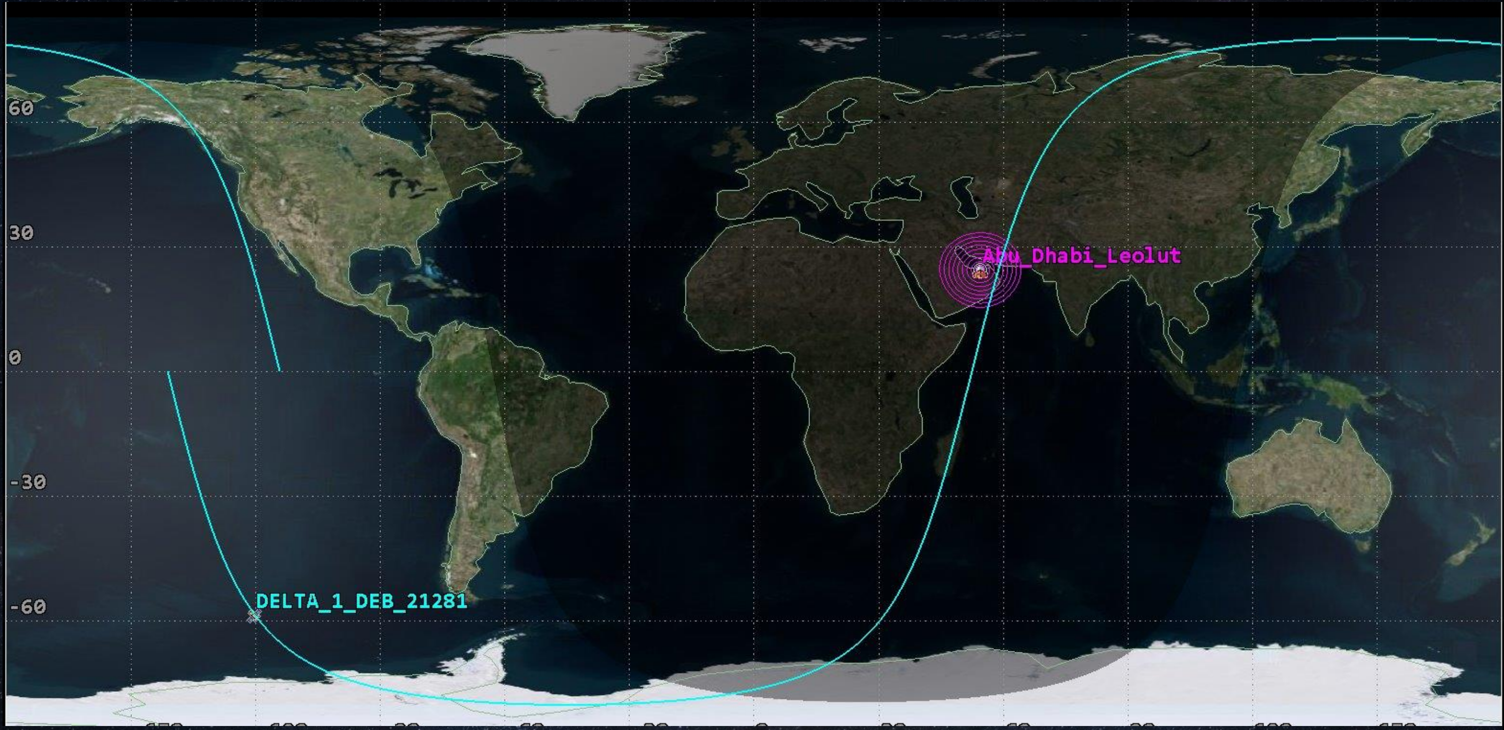


2.3 Data Handling and Comms

Communications Architecture

- Debris Selection: DELTA 1 DEB
- Ground Station: Abu Dhabi LEOLUT
  - 38 Passes/Week available
  - Avg Contact Duration 876.223s
- Type of Data:
  - Telemetry/Status data (50KB/pass)
  - Structural Test data (10MB/pass)

	Downlink	Uplink
Frequency [GHz]	1.5	2.0
Xmtr. Power [W]	0.5	0.3
Bitrate [Mbps]	5.3	5.09
Link Margin [dB]	10.17	7.80



Power

Power Budget

Maximum instantaneous power consumption during solar illumination and eclipse

- During mechanical & machining operations, average power consumption is 305.93 Watts

- During eclipse times, most functionality is in sleep mode. Thermal and power systems are allocated more power to keep payload thermally regulated

Power Budget (daylight)		
Venus X Class Bus	**% Breakdown**	**Wattage [W]**
Thermal Control	30%	47.7133
Attitude Control	11%	17.4949
Power	3%	4.7713
CDS	12%	19.0853
Communications	13%	20.6758
Propulsion	1%	1.5904
Battery Charging	5%	7.9522

Prometheus Payload	% Breakdown	Wattage [W]
Thermal Control	5%	14.2478
Attitude Control	0%	0.0000
Power	1.5%	4.2743
CDS	4%	11.3982
Communications	5.0%	14.2478
Propulsion	0%	0.0000
Mechanism	50.0%	142.4779
Total Illumnation Power	**Pi**	**305.9292**

Power Budget (Eclipse)		
Venus X Class Bus	**% Breakdown**	**Wattage [W]**
Thermal Control	50%	79.5221
Attitude Control	2%	3.1809
Power	4%	6.3618
CDS	4%	6.3618
Communications	2%	3.1809
Propulsion	1%	1.5904
Battery Charging	0%	0.0000

Prometheus Payload	% Breakdown	Wattage [W]
Thermal Control	3%	8.5487
Attitude Control	0%	0.0000
Power	6%	17.0973
CDS	2%	5.6991
Communications	0%	0.0000
Propulsion	0%	0.0000
Mechanism	0%	0.0000
Total Eclipse Power	**Pe**	**131.5430**

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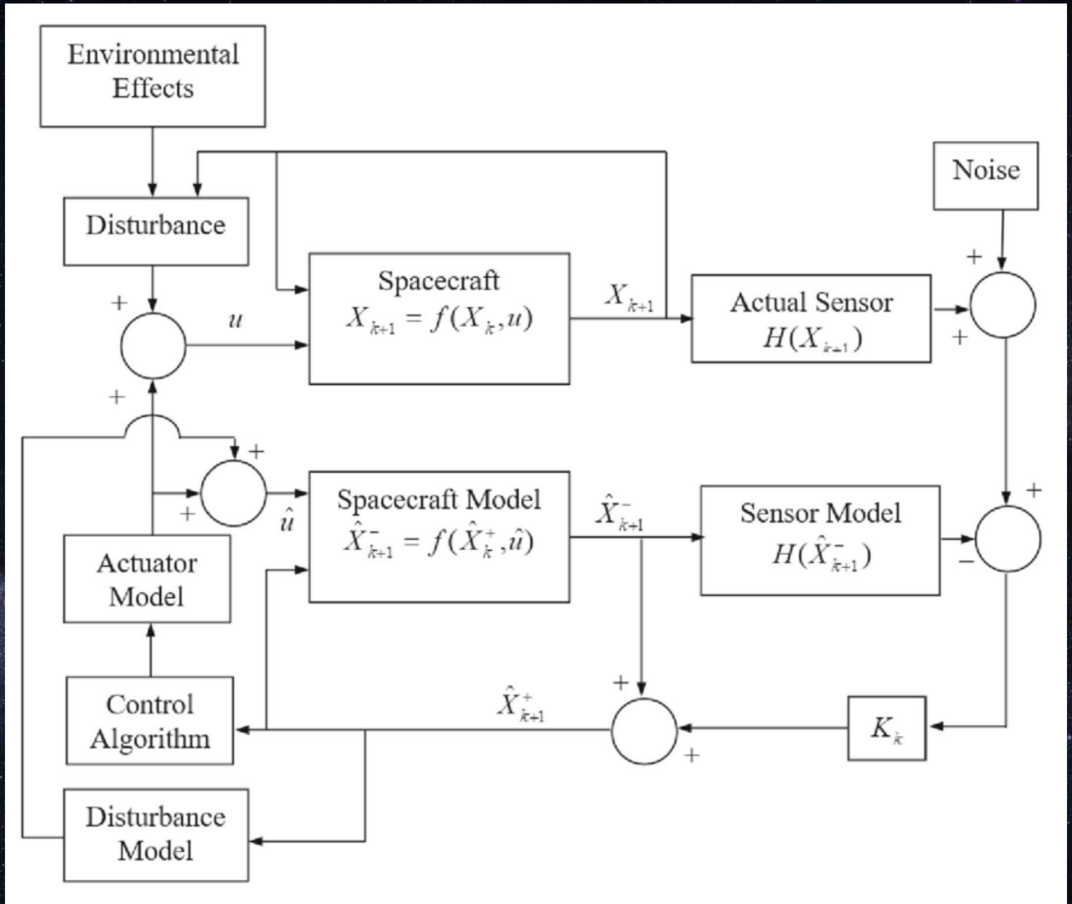
Guidance, Navigation, and Control

Control Pipeline

- AI control methods
  - Efficient
  - Flexible
- Extended Kalman Filter for state estimation

- Sensors:
  - Sun sensor
  - Gyroscopes
  - Magnetometers
  - Cameras



Mekky, T., and Habib, A., "Artificial Intelligence for spacecraft guidance, navigation, and control: A state-of-the-art - aerospace systems," *SpringerLink* Available: https://link.springer.com/article/10.1007/s42401-022-00152-y.

Mass Budget

Payload on-board weight by part

- Bottoms-up to Top-Down budgeting technique
- Underbudget to allow debris weight onto payload without exceeding mass constraints

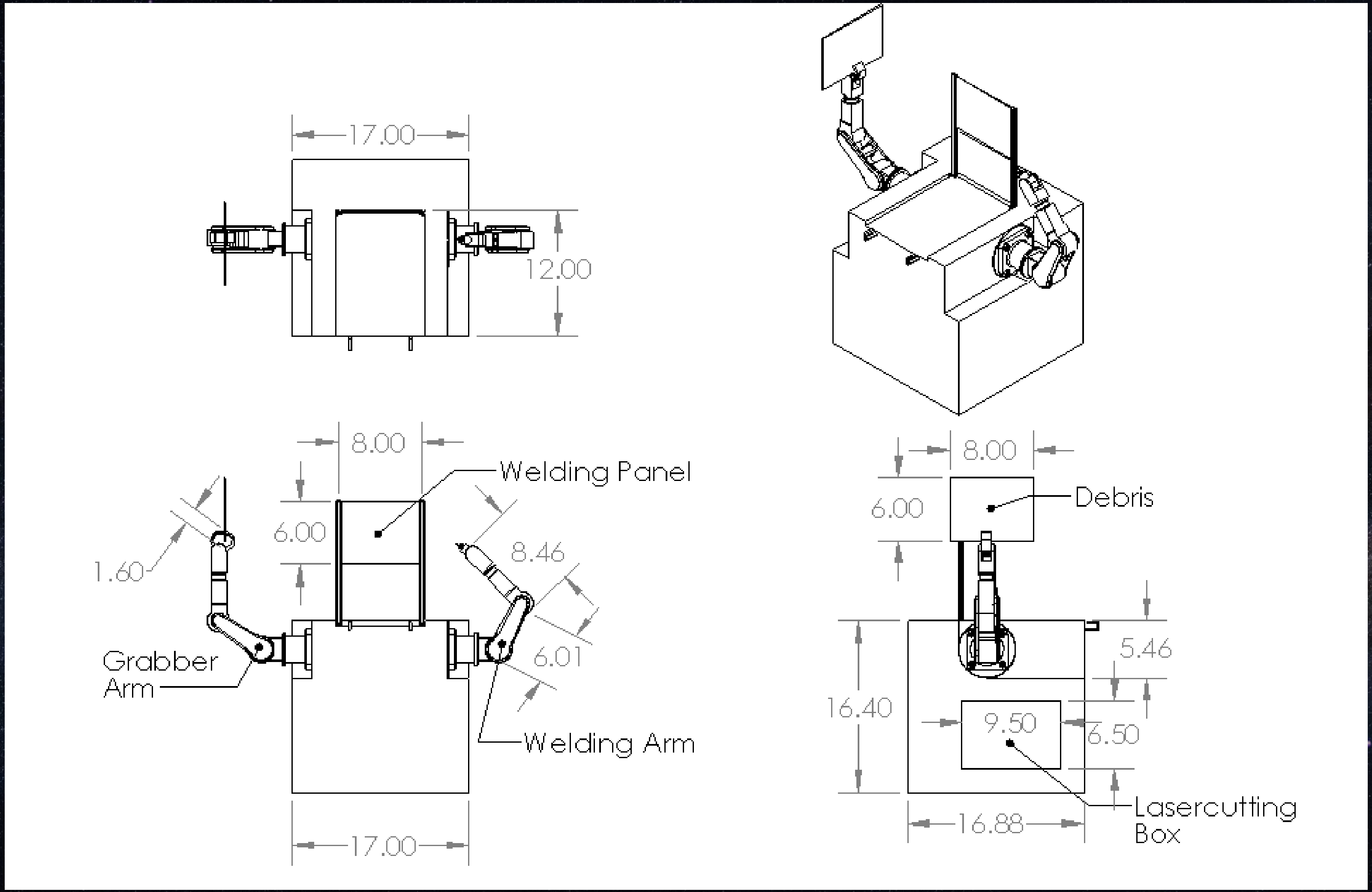
	TRL	Quantity	Unit Mass [kg]	Total Mass [kg]	% Breakdown
Thermal				4	8.66%
C&DH					
Computer	9	1	0.032	0.032	0.07%
Wiring	9	0.75	0.087	0.06525	0.14%
Battery					
Battery	4	2	10	20	43.28%
Converter	4	2	1.322	2.644	5.72%
Structure					
Linear Actuators	7	2	0.0055	0.011	0.02%
Rotational Actuators	6	2	0.45	0.9	1.95%
EBW	8	1	1.8	1.8	3.90%
Grabbing Hands	1	2	0.04	0.08	0.17%
Base Payload	9	1	16.68	16.68	36.09%
				46.21225	100.00%

[redacted]

[redacted]

3-View of Payload

Size Constraint Validation



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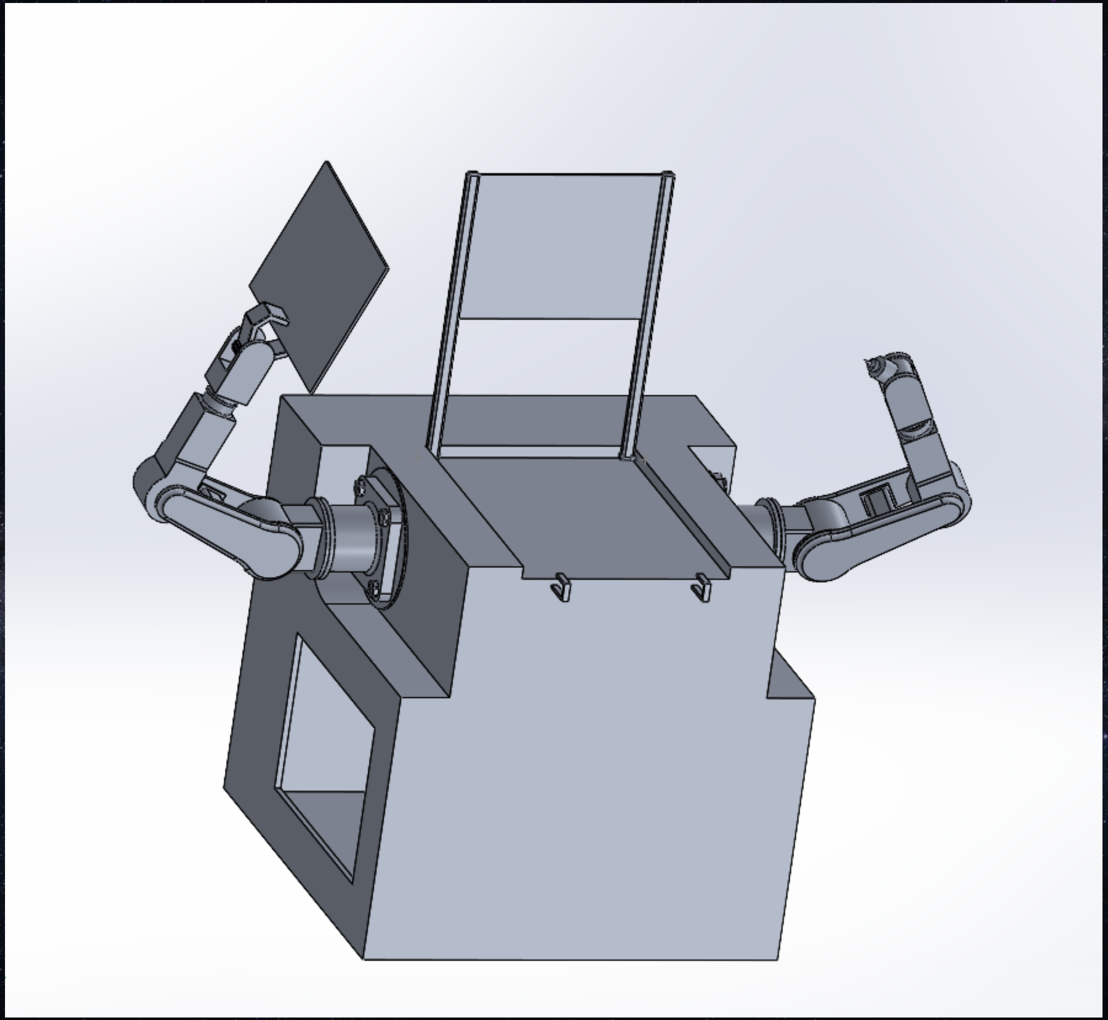
Payload Dimensions (in inches)

Prometheus Payload

Body Overview

- **Primary Material:**
  - Aluminum 6061 T6
    - NASA approved metal for space flight
      - Low outgassing
      - Good metal for welding
- **Utilizes 2 Robotic Arms**
  - Will be able to pack into the body of the satellite for compaction
  - One will have a grabber at the end
  - The other will have the electron beam welder



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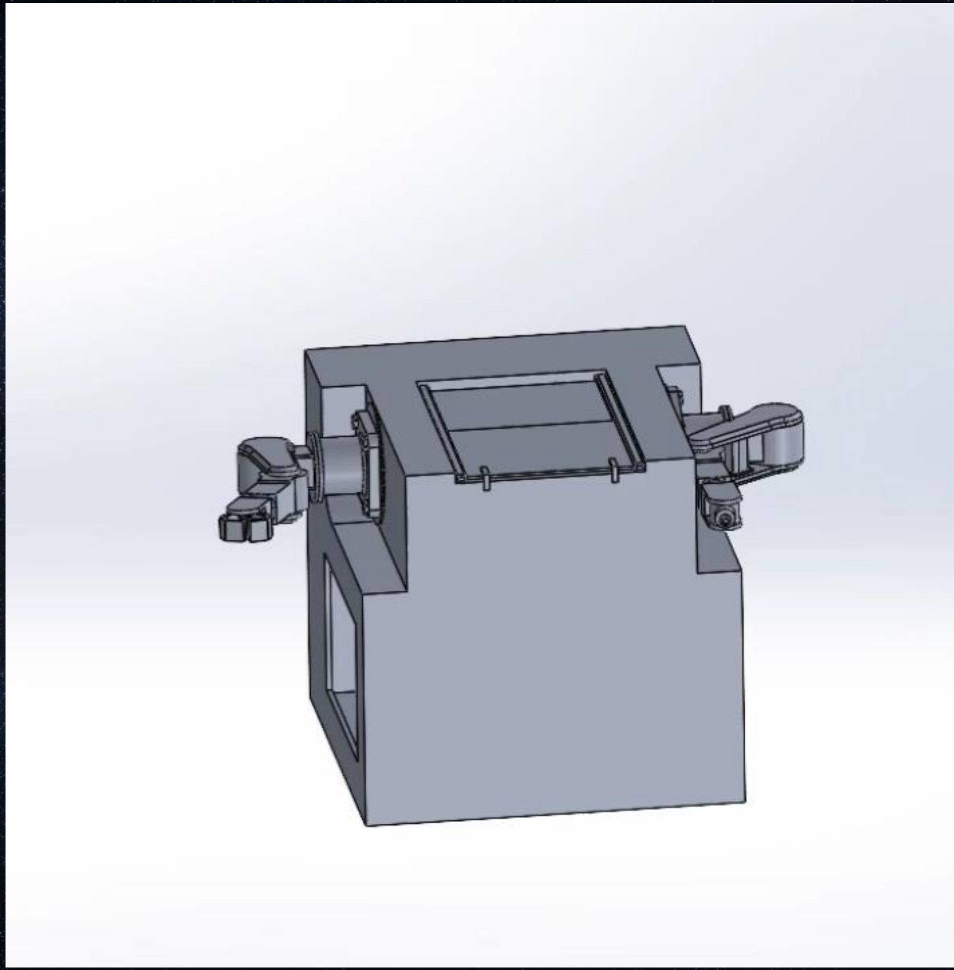
2.1 Animation of Key Operating Sequence

Payload Operations



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Operations: (1) Rendezvous with Debris, (2) Laser Cutting, (3) Welding

3.2 Technology Gap Assessment

Involving size/mass constraints and adaptive decision-making for autonomous operations

- Current fiber laser cutters are too large for practical payload integration.
- Servicing systems require human input and lack real-time adaptive decision-making and autonomous monitoring.
- Existing batteries are too heavy or lack sufficient energy density to support extended laser cutting and welding without frequent recharging.

3.3 Biggest Challenges Encountered

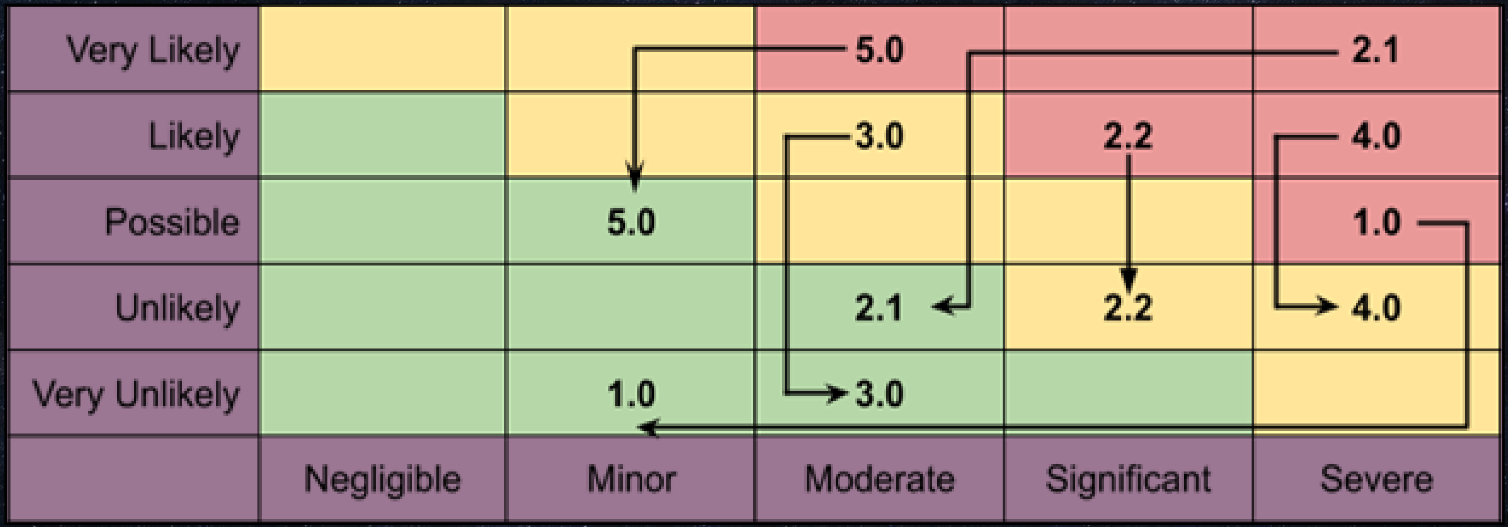
Concern for power and heating during operation and proper debris mitigation

- **Lack of Heat Dissipation in Fiber Laser Cutter and Welder**
  - **Challenge**: No solution was developed to prevent overheating in the fiber laser cutter and welder. Excessive heat could melt the gun tips and potentially interfere with sensitive payload electronics. Without a proper heat dissipation system, prolonged operation posed a risk to both equipment and overall mission success.
- **Power Supply and Conversion Issues**
  - **Challenge**: The battery does not have sufficient capacity to support both welding and laser cutting operations. Additionally, a suitable space-grade DC-DC converter that met operational requirements could not be found
- **Lack of Active Debris Mitigation During Servicing**
  - **Challenge**: There was no active strategy in place to manage debris generated during servicing operations. Uncontrolled debris could pose a hazard to both the payload and surrounding components. To address this, all laser cutting shall be conducted within the payload bay to contain debris and minimize risks.

1.5 Risks

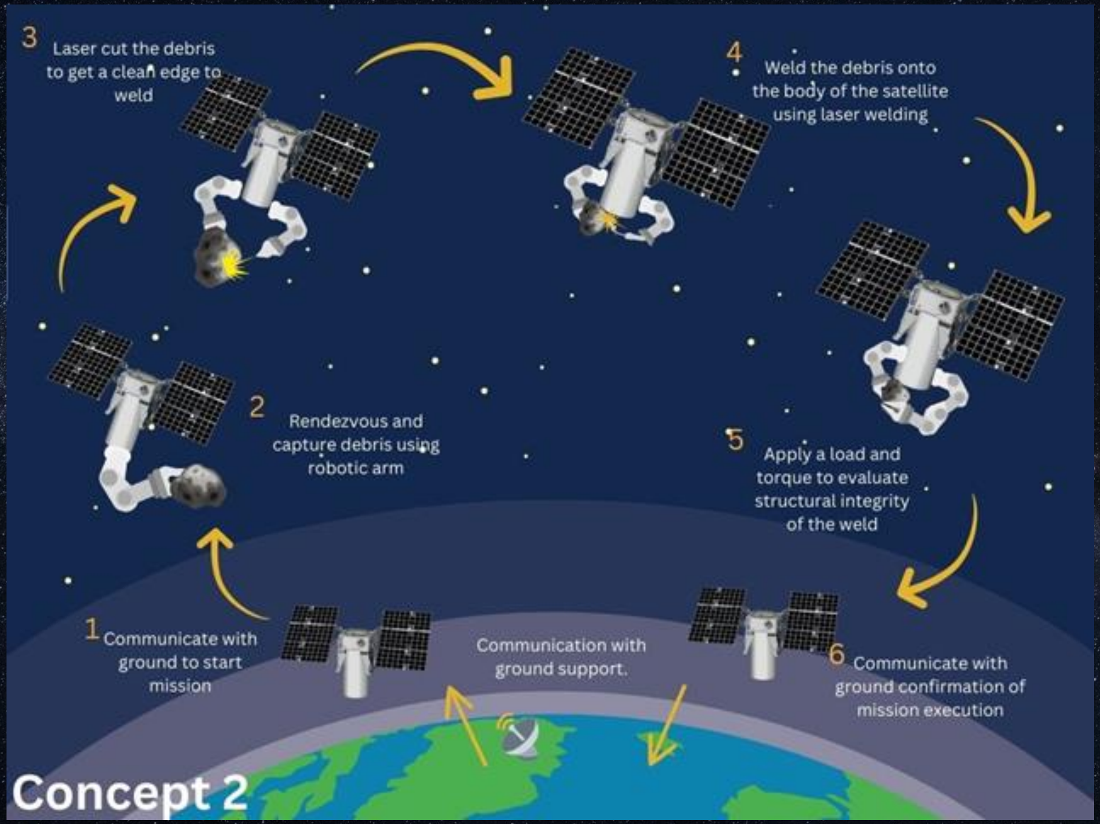
Mitigation Strategies and Effects

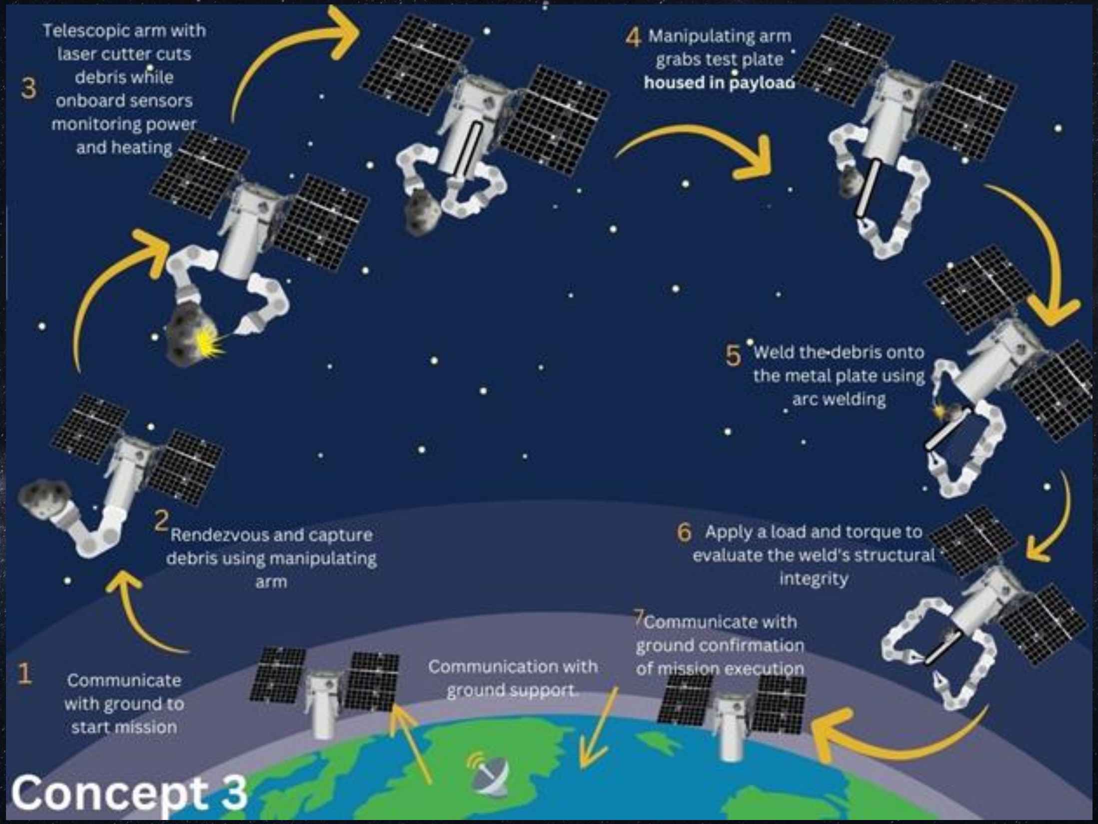
Risks	Mitigation Strategy
1. Autonomy Fail	Manual Override Contingency
2. Hit Debris	
2.1 Self-generated Debris	Contain laser cutting and welding procedures inside the payload
2.2 External Debris	Rendezvous with isolated piece of debris
3. Insufficient Battery Charge	Add additional battery
4. Overheated internal parts	Increase radiation hardening and thermal coverage near laser and welding arm
5. Low TRL	Additional component testing with in-space conditions



3.1 Innovative Concepts

Additional Concepts





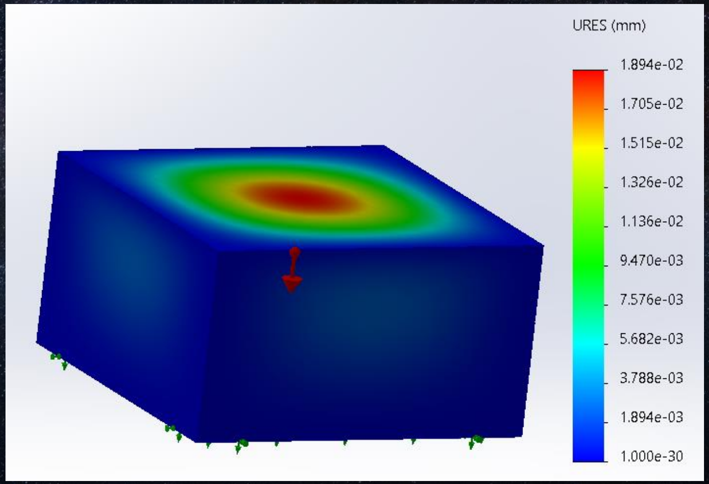
Different methods of welding and plate management

1.6 Path to PDR

Subsystem Decomposition

- **Cosmic Capstone Challenge**
  - **Venus X Class**
    - **Power** – Vraj Patel
    - **Thermal** – Bryce Pochron
    - **GNC** – Joe Messner
    - **Structures** – Katie Blyler
    - **Propulsion** – Dylan Nastanski
    - **Communication** – Yasmine Kadire
    - **Command and Data Handling** – Yasmine Kadire
    - **Prometheus**
- **Launch Vehicle** – Katie Blyler
- **Ground Station** – Joe Messner

Venus Class Bus FEA



Subsystem Decomposition and Analysis for Venus X Class Bus Complete

1.6 Path to PDR

Future Work

- Advanced Arm Control Methods Development
- Detailed Electron Beam Welding Gun Integration Modifications
- Increased Technology Readiness Levels for Power System Components
- Preparing for End of Decade
  - Bill of Materials
  - Manufacturing
  - Prototype Testing
  - Advancements in AI control methods

Prometheus Payload: Bill of Materials

	TRL	Quantity	Unit Price	Total Cost
C&DH				
Computer	9	1	$50,000	$50,000
Wiring	9	0.75	$500	$375
Battery				
Battery	4	2	$145	$290
Converter	4	2	$1,435	$2,870
Structure				
Linear Actuators	7	2	$1,586	$3,172
Rotational Actuators	6	2	$3,456	$6,912
EBW	8	1	$100,000	$100,000
Grabbing Hands	1	0.04	$4	$0.16
Base Payload	9	16.64	$4	$67
Payload Total				**$163,686**
Launch Vehicle		1	$ 52 Million	$52 Million

Lessons Learned

Classroom concepts applied technically

Applying Technical Skills

- Power
- Thermal
- Structures
- Orbit Analysis

Group Specific

- Professional workplace environment
- Effective communication
- Task delegation

Summary

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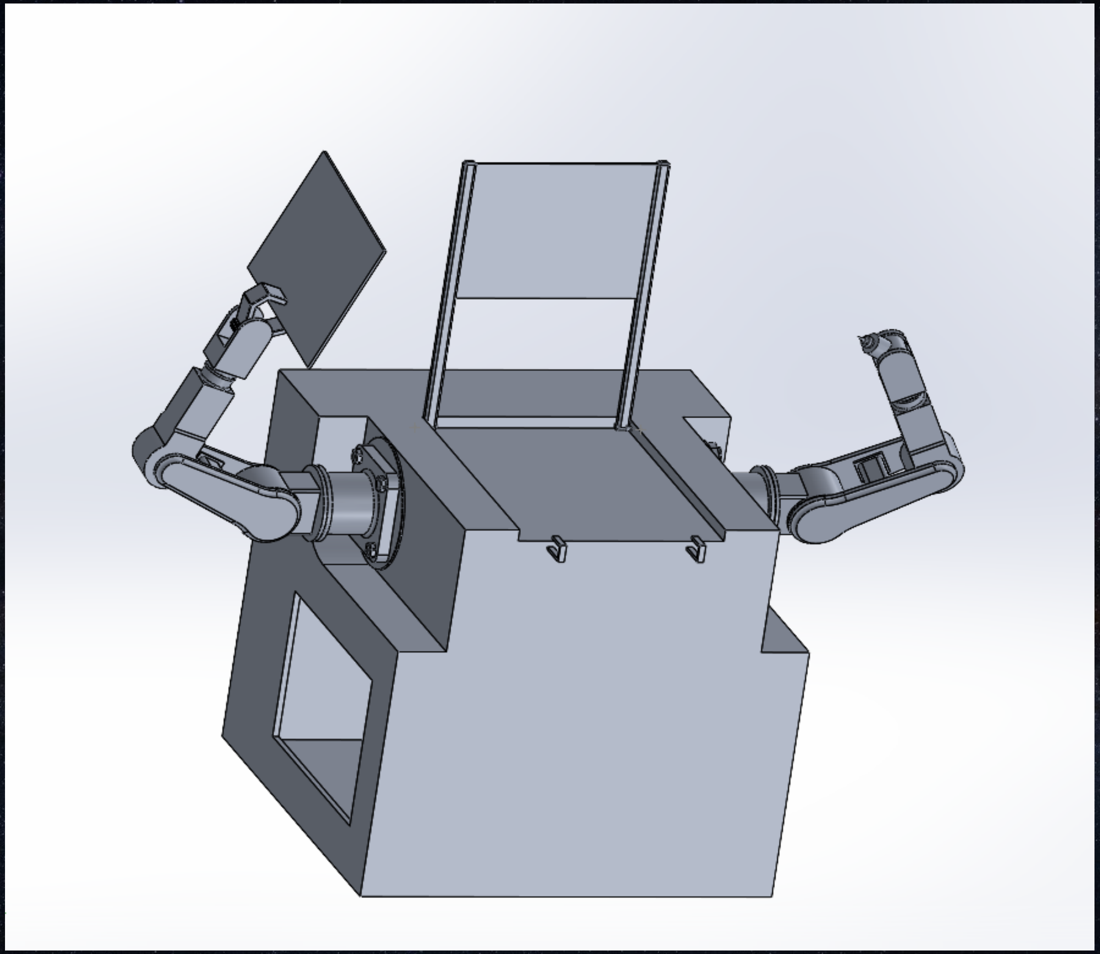
- Key Innovations
  - Semi-Autonomous Laser Cutter
  - Electron Beam Welder Manipulation
  - Debris Mitigation Plan
- Impact to ISAM
  - Advancements in Welding and Laser Cutting Automation
  - In-Space Testing of Lightweight Electron Beam Emission System



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Questions

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Questions?

Backup Slides

Macro Mission Architecture

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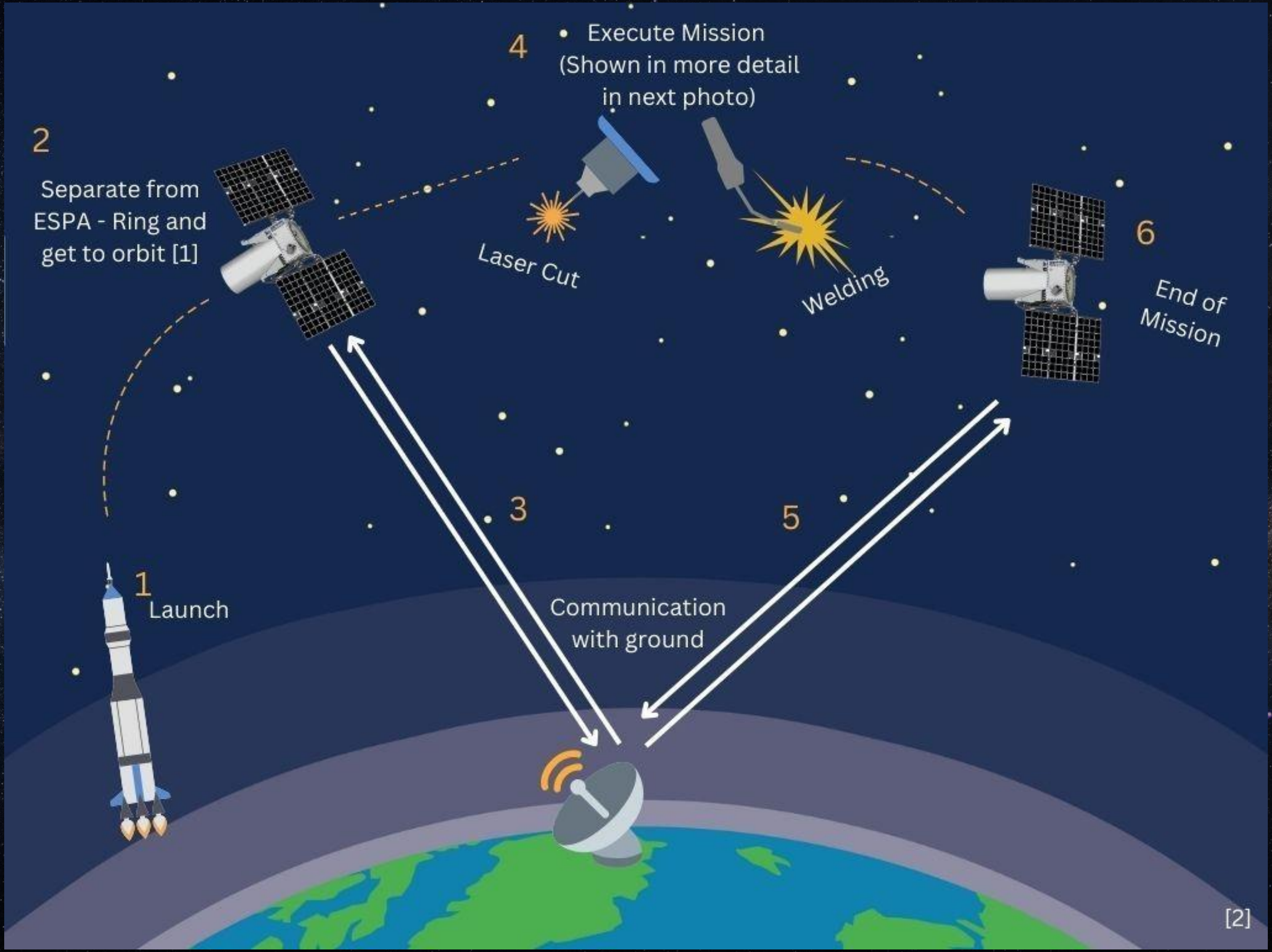
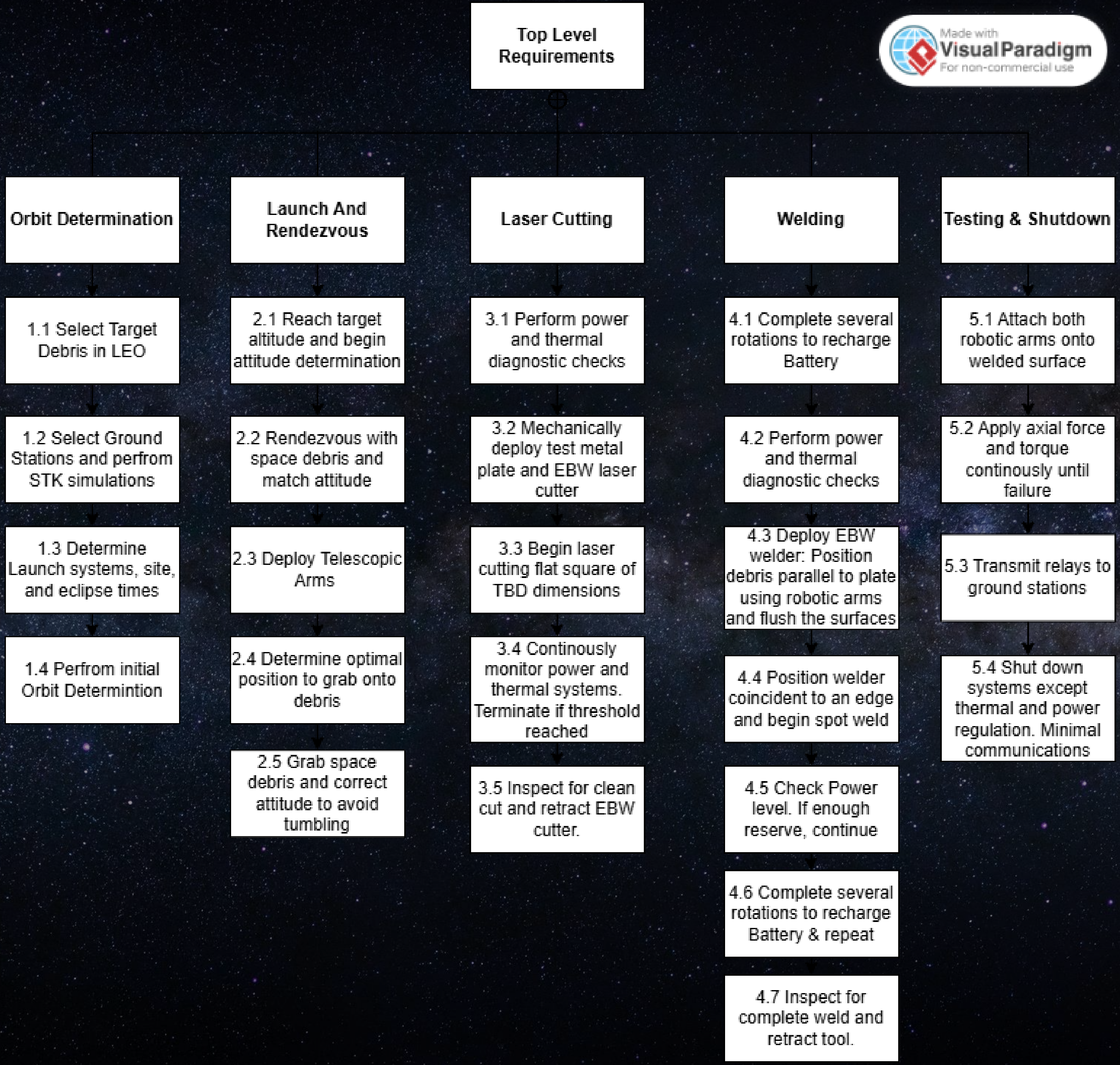


Functional Architecture



Deployed and Launch Configurations

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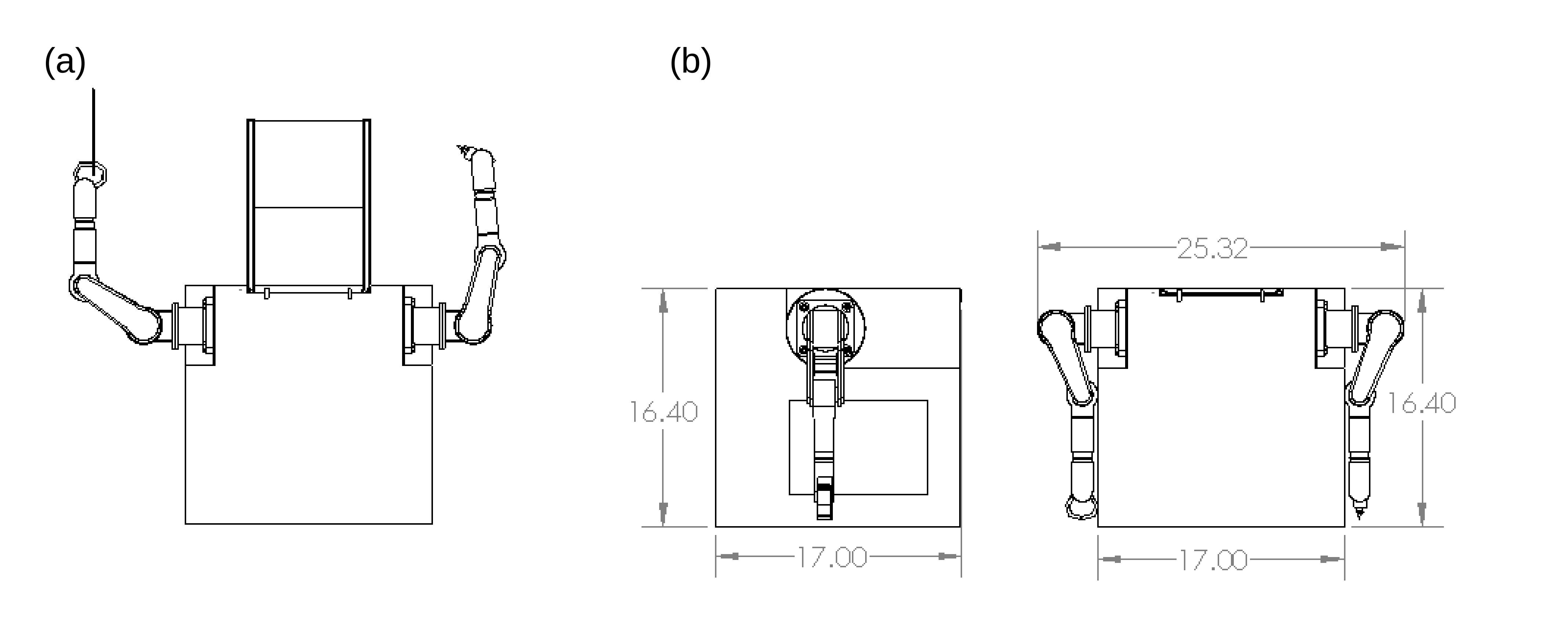

Final Design: (a) payload configuration once deployed and in use (b) payload configuration for launch (dimensions in inches)

Payload Material – Trade Study

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	Weight	Goal	Aluminum Al 6061-T4 [18]	Titanium Ti-6Al-4v [19]	Stainless Steel SS321 [20]
Density	30%	Min	2.7 g/cm^3	4.43 g/cm^3	7.9 g/cm^3
Normalized Value			1	0.6673	0
Weldability	30%	Max	3	2	1
Normalized Value			1	0.5	0
Young's Modulus	5%	Max	69 GPa	114 GPa	193 GPa
Normalized Value			0	0.3629	1
Ultimate Tensile Strength	5%	Max	240 MPa	950 MPa	515 MPa
Normalized Value			0	1	0.3873
Melting Point	25%	Min	650 °C	1660 °C	1425 °C
Normalized Value			1	0	0.7673
Coefficient of Thermal Expansion	5%	Min	23.6 µm/(m*K)	9.7 µm/(m*K)	18.6 µm/(m*K)
Normalized Value			0	1	0.6403
Total			0.85	0.468335	0.58134

Final Choice: Aluminum Al 6061-T4 for weldability and low density

Linear Actuator– Trade Study

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	Weight	Goal	Xeryon Lightweight Linear Actuators [7,8,9]	UltraMotion Servocylinder [10]	Firgelli Micro Pen Actuator with Feedback [11]
Mass	25%	Min	5.5 g	1905.1 g	81 g
Normalized Value			1	0	0.9605
Power Consumption	25%	Min	5W	180 W	3.6 W
Normalized Value			0.9921	0	1
Volume	15%	Min	1.8 cm^3	988.1 cm^3	1.47 cm^3
Normalized Value			0.9997	0	1
Extension Length	10%	Max	11.8 in	1.75 in	3.9 in
Normalized Value			1	0	0.2139
Cost per Actuator	5%	Min	$1586	$3,208	$135.95
Normalized Value			0.5280	0	1
Technology Readiness Level	20%	Max	7	9	4
Normalized Value			0.6000	1	0
Total			0.8944	0.2000	0.7115

Final Choice: Zeryon Lightweight Linear Actuators due to size and power requirements

Rotary Actuator– Trade Study

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	Weight	Goal	Xeryon Precision Rotation Stages [13, 14, 15]	MOOG Model HT1 Rotary Incremental Actuator [16]	Space Lock Rotary Actuator [17]
Mass	20 %	Min	0.450 kg	0.9525 kg	0.8 kg
Normalized Value			1	0	0.3035
Power Consumption	30 %	Min	5 W	10 W	2.7 W
Normalized Value			0.6849	0	1
Volume	10 %	Min	10.0125 cm^3	432.4 cm^3	202.2 cm^3
Normalized Value			1	0	0.5450
Technology Readiness Level	40 %	Max	6	9	6
Normalized Value			0	1	0
Total			0.5055	0.4	0.4152

Final Choice: Zeryon Precision Rotation States due to size and power requirements

Computer – Trade Study

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	Weight	Goal	Xiphos Q7s	iXblue Muons	EnduroSat OBC
Power	45%	Max	5-15W	10-20W	1-5W
Normalized Value			0.333	1	0
Mass	35%	Min	32g	60g	130g
Normalized Value			1	0.286	0
Flight History	20%	Max	1	0	1
Total	100%		0.6998	0.5501	0.2

Final Choice: Xiphos Q7s

Electron Beam Welding Gun – Trade Study

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	Weight	Goal	Paton New EBW Gun	Skylab M-551	Universal Hand Tool	Salyut-7 Versatile Hand Tool
Accel. Voltage	20%	Max	10 kV	20 kV	10 kV	5 kV
Normalized Value			0.667	1	0.667	0
Beam Current	20%	Max	250 mA	80 mA	100 mA	100 mA
Normalized Value			1	0	0.1176	0.1176
Beam Power	35%	Max	2.5 kW	1.6 kW	1 kW	0.5 kW
Normalized Value			1	0.55	0.25	0
Dimensions (L/W/H) in mm	10%	Min	220/80/290	400 mm sphere	----	290/135/230
Normalized Value			0	1	----	0.01334
Mass	15%	Min	1.8 kg	20 kg	4.5 kg	3.5 kg
Normalized Value			1	0	0.8516	0.9066
Total			0.8334	0.4925	0.37216	0.160844

Final Choice: Paton New Electron Beam Welding Gun

Prometheus
BLYLER · KADIRE · MESSNER · NASTANSKI · PATEL · POCHRON

Laser Cutting Method - Trade Study

Prometheus

Criteria	Weight	Goal	CO2 Laser	Fiber Laser	Neodymium Yttrium Laser
Power Efficiency	25%	Max	5-20%	30-50%	20%
Normalized Value			0	1	.273
Beam Quality	15%	Min	.25mm	.015mm	.2mm
Normalized Value			0	1	.212
Cutting Speed	5%	Max	3.6 m/min	9m/min	2m/min
Normalized Value			.229	1	0
Material Compatibility	5%	Max	1	3	2
Normalized Value			0	1	.5
Size and Weight	15%	Min	3	1	1
Normalized Value			0	1	1
Vacuum Suitability	15%	Max	1	1	3
Normalized Value			0	0	1
Operational Lifetime	5%	Max	2000 hours	25000 hours	10,000-15000
Normalized Value			0	1	.4565
Cost	5%	Min	3	1	2
Normalized Value			1	0	.5
Totals	100%		.06145	.85	.472875

Final Choice: Ytterbium Doped Fiber Laser Cutter

Ground Station – Trade Study

Prometheus

	Weight	Goal	Abu Dhabi Leolut	Clewiston	Tidbinbilla
Passes per week	30%	Max	38	35	40
Normalized Value			0.600	0	1
Min Contact Duration	10%	Max	47.745 s	23.908 s	0.938 s
Normalized Value			1	0.490	0
Max Contact Duration	20%	Max	1143.981 s	1139.145 s	1047.855 s
Normalized Value			1	0.950	0
Avg Contact Duration	40%	Max	876.223 s	864.221 s	567.062
Normalized Value			1	0.961	0
Total			0.88	0.6234	0.3

Final Choice: Abu Dhabi

Launch Vehicle – Trade Study

CONSORTIUM FOR SPACE MOBILITY AND ISAM CAPABILITIES

Prometheus

	Weight	Goal	SpaceX Falcon 9 [36, 37]	Rocket Lab Electron [38]	Relativity Terran 1 [39]
Reusability	20%	Max	3	2	3
Normalized Value			1	0	1
Reliability	30%	Max	446 completed missions	61 completed missions	1 completed mission
Normalized Value			1	0.1325	0
Payload Mass to LEO	30%	Max	22,800 kg	300 kg	1,250 kg
Normalized Value			1	0	0.0422
ESPA Ring Compatibility	10%	Max	3	3	3
Normalized Value			1	1	1
Estimated Cost	10%	Min	$52 million	$5 million	$12 million
Normalized Value			0	1	0.8511
Total			0.900	0.23975	0.3978

Final Choice: SpaceX, Falcon 9 Rocket – Launched Out of Vandenberg Airforce Base

Propulsion – Trade Study

Prometheus

	Target	Weight	Monarc-90	MRE – 5.0	MR-107	CHT-20
Mass (kg)	Min	25%	1	1.5	0.74	0.395
Normalized Value			0.4525	0	0.6878	1
Length (m)	Min	15%	0.3	0.264	0.213	0.195
Normalized Value			0	0.3429	0.8286	1
Thrust (N)	Max	35%	90	28	296	24.6
Normalized Value			0.2410	0.0125	1	0
Isp (s)	Max	25%	235	232	232	230
Normalized Value			1	0.4	0.4	0
Total			0.4475	0.1558	0.7462	0.4

Final Choice: Aerojet MR-107

GNC – Trade Study

Prometheus

	Weight	Goal	Stability	Optimization	AI
Algorithm Flexibility	30%	Max	1	3	2
Normalized Score			0	1	0.5
Algorithm Efficiency	40%	Max	2	1	3
Normalized Score			0.5	0	1
Algorithm Stability and Robustness	30%	Max	3	1	2
Normalized Score			1	0	0.5
Total			0.5	0.3	0.7

Final Choice: AI Based Methods

Link Budget (Downlink)

Prometheus

DOWNLINK				
Freq.	f	Ghz	input	**1.5**
Xmtr Pwr	P	W.	input	**0.500**
Xmtr Pwr	P	dbW	10 log(P)	-3.01
Xmtr line loss	L_l	dB	input	**-1.00**
Xmtr Ant. Beamwidth	q_t	deg	Eq. (13-19)	64.746
Peak Xmt. Ant. Gain	G_{pt}	dB	Eq. (13-20)	8.08
Xmt. Ant. Diam.	D_t	m	input	**0.21**
Xmt. Ant. Pointing Error	e_t	deg	input	**0.00**
Xmt. Ant. Pointing Loss	L_{pt}	dB	Eq. (13-21)	0.00
Xmt Ant. Gain	G_t	dB	$G_{pt}+L_{pt}$	8.08
EIRP	EIRP	dB	$P+L_l+G_t$	4.07
Prop. Path Length	S	km	input	**1.087E+03**
Space Loss	L_s	dB	Eq. (13-23a)	-156.94
Prop. & Polariz. Loss	L_a	dB	Fig. 13-10	**-0.20**
Rcv. Ant. Diam.	D_r	m	input	**2.30**
Peak Rcv. Ant. Gain	G_{rp}	dB	Eq. (13-18a)	28.82
Rcv. Ant. Beamwidth	q_r	deg	Eq. (13-19)	5.91
Rcv. Ant. Pointing Error	e_r	deg	input	**1.20**
Rcv. Ant. Pointing Loss	L_{pr}	dB	Eq. (13-21)	-0.49
Rcv. Ant. Gain	G_r	dB	$G_{rp}+L_{pr}$	28.33
System Noise Temp.	T_s	K	input (using Table 13-10)	**221.00**
Data Rate	R	bps	input	**5.29E+06**
Est. E_b/N_o (1)	E_b/N_o	dB	Eq. (13-13)	13.17
Bit Error Rate	BER	--	input	**1.0E-04**
Rqd. E_b/N_o (2)		dB	Fig. 13-9 (BPSK, R-1/2 Viterbi)	**3.00**
Implementation Loss (3)		dB	input (standard estimate)	**0.00**
Margin		***dB***	***(1)-(2)+(3)***	***10.17***

Link Budget (Uplink)

Prometheus

UPLINK				
Freq.	f	Ghz	input	**2.0**
Xmtr Pwr	P	W.	input	**0.3**
Xmtr Pwr	P	dbW	10 log(P)	-6.02
Xmtr line loss	L_l	dB	input	**-1.00**
Xmtr Ant. Beamwidth	q_t	deg	Eq. (13-19)	4.565
Peak Xmt. Ant. Gain	G_{pt}	dB	Eq. (13-20)	31.11
Xmt. Ant. Diam.	D_t	m	input	**2.30**
Xmt. Ant. Pointing Error	e_t	deg	input	**1.20**
Xmt. Ant. Pointing Loss	L_{pt}	dB	Eq. (13-21)	-0.83
Xmt Ant. Gain	G_t	dB	$G_{pt}+L_{pt}$	30.28
EIRP	EIRP	dB	$P+L_l+G_t$	23.26
Prop. Path Length	S	km	input	**1.087E+03**
Space Loss	L_s	dB	Eq. (13-23a)	-159.19
Prop. & Polariz. Loss	L_a	dB	Fig. 13-10	**-0.20**
Rcv. Ant. Diam.	D_r	m	input	**0.21**
Peak Rcv. Ant. Gain	G_{rp}	dB	Eq. (13-18a)	10.28
Rcv. Ant. Beamwidth	q_r	deg	Eq. (13-19)	50.00
Rcv. Ant. Pointing Error	e_r	deg	input	**0.00**
Rcv. Ant. Pointing Loss	L_{pr}	dB	Eq. (13-21)	0.00
Rcv. Ant. Gain	G_r	dB	$G_{rp}+L_{pr}$	10.28
System Noise Temp.	T_s	K	input (using Table 13-10)	**614.00**
Data Rate	R	bps	input	**5.09E+05**
Est. E_b/N_o (1)	E_b/N_o	dB	Eq. (13-13)	4.15
Bit Error Rate	BER	--	input	**1.2E-01**
Rqd. E_b/N_o (2)		dB	Fig. 13-9 (BPSK, R-1/2 Viterbi)	**3.00**
Implementation Loss (3)		dB	input (standard estimate)	**3.00**
Margin		***dB***	***(1)-(2)+(3)***	*7.80*

Orbital Analysis

Prometheus

- Chosen Debris: DELTA 1 DEB
  - Relatively isolated
  - LEO
- Will remain on DELTA 1 DEB's orbit for the remainder of the mission
- Orbital elements determined in STK

Orbital Elements	
Semi-Major Axis	7500 km
Eccentricity	0.005618
Inclination	99.940°
RAAN	350.223°
Argument of Perigee	20.342°
Orbital Period	107.73 min