COSMIC

THE POWER OF COLLABORATION

COSMIC Capstone Challenge: Final Briefing

Eta Leonis, The Pennsylvania State University
D.I.S.C. Mission: Demonstration of In-Space Coatings

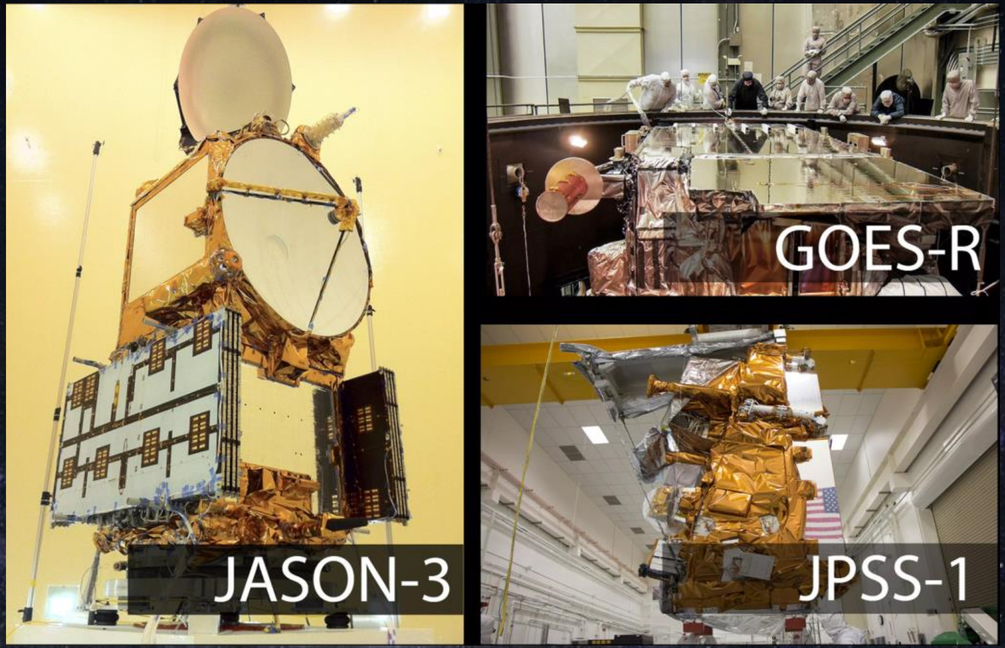
Students: Nicholas Luis, Jason Lu, Miguel Moya, Nicholas Sernberger, Noah Smargiassi, Kaiden Smith, Luke Verdi
Advisor: Sara Lego
Mentor: Brian Holt

April 16, 2025

Executive Summary

Demonstration of In-Space Coatings

- Spacecraft require coatings to better survive the space environment
  - A thin coating, or thin film, can significantly alter the material properties
- Currently no way to apply or reapply coatings while in space
  - All coatings are applied before launch
  - Coatings are critical for all future ISAM capabilities
    - Service expensive satellites
    - Coatings are better when done in space
- Mission: technology demonstration for autonomously manufacturing thin film coatings in space
  - Operation 1: Grab onto objects
  - Operation 2: Coat objects (Aluminum and Chromium)
  - Operation 3: Analyze surface properties



“As Good As Gold: Are Satellites Covered in Gold Foil?”, National Oceanic and Atmospheric Administration, Aug. 2016, https://www.nesdis.noaa.gov/news/good-gold-are-satellites-covered-gold-foil

Team Eta Leonis

Demonstration of In-Space Coatings

Nicholas Luis

Jason Lu

Miguel Moya

Noah Smargiassi

Kaiden Smith

Luke Verdi

Nicholas Sernberger

2.4 Systems Engineering Milestones

Demonstration of In-Space Coatings

Sept. 12th 2024
Nicholas Luis was selected as program manager

Sept. 26th 2024
Chose ISAM capabilities:
- Object handling
- In-Space Coatings
- Surface characterization

Oct./Nov. 2024
Defined system requirements, developed a functional analysis and top level requirements

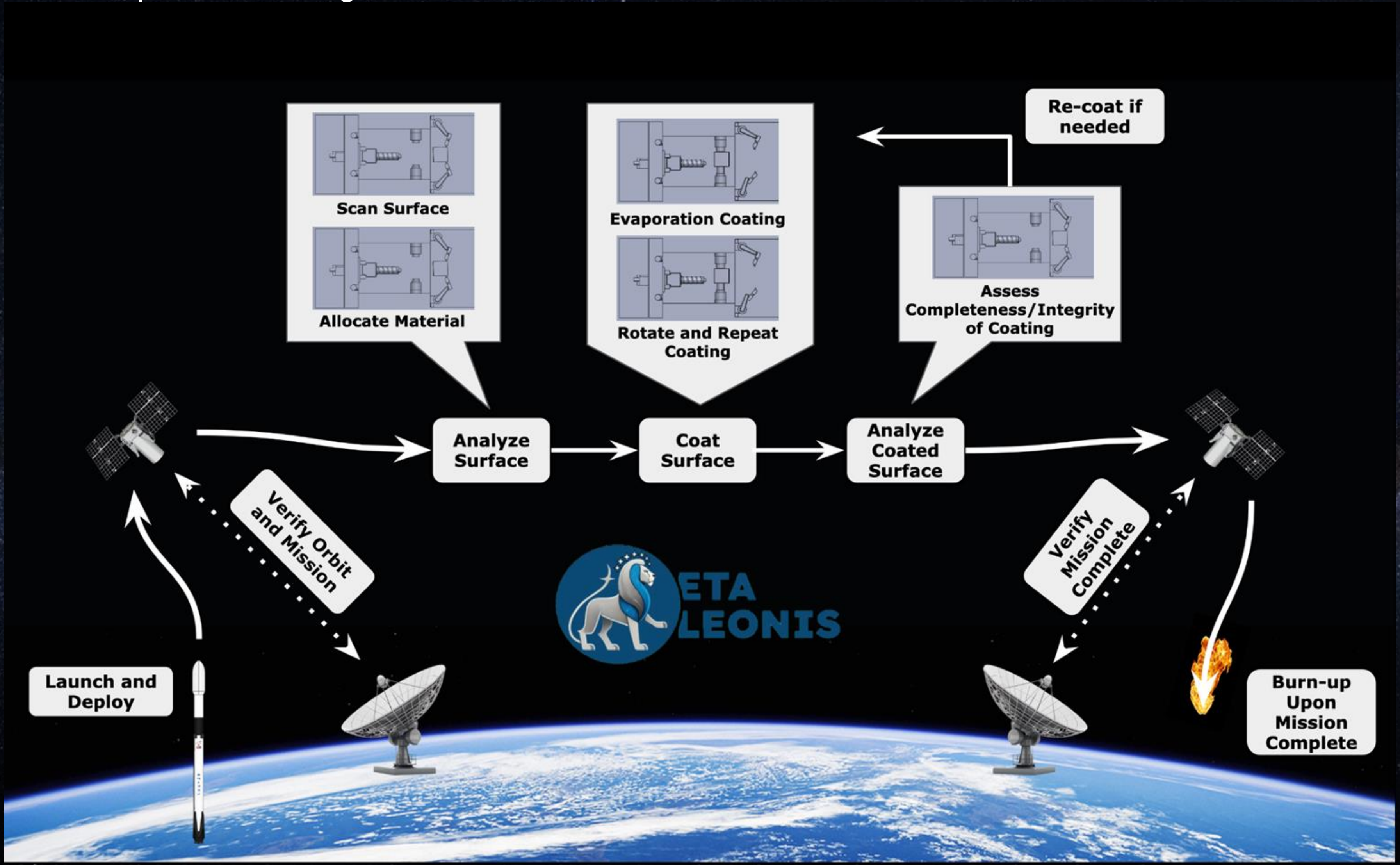
Dec. 2024
Conducted a full CONOPS, completed C3 flash talk, made final mission concept selection, and conducted a system requirements review

Mar. 18th 2025
Finalized conceptual design and integrated all subsystems together to meet requirements

Apr. 2nd 2025
Developed a Path to PDR

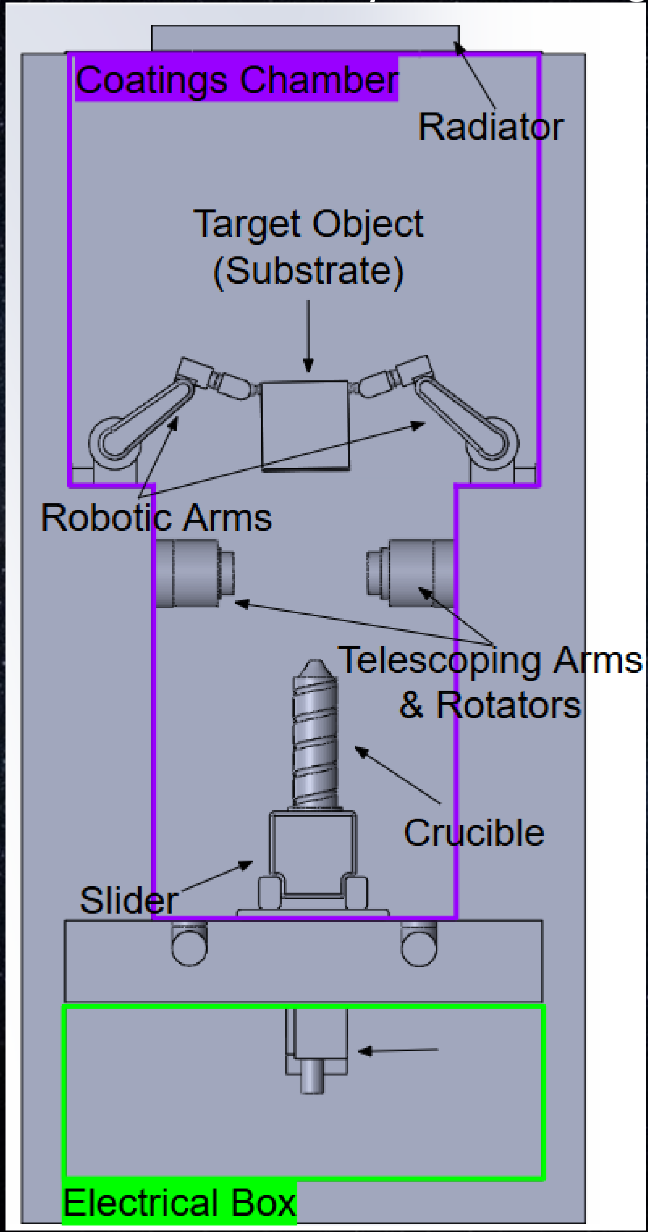
2.2 Storyboard of Complete Operation

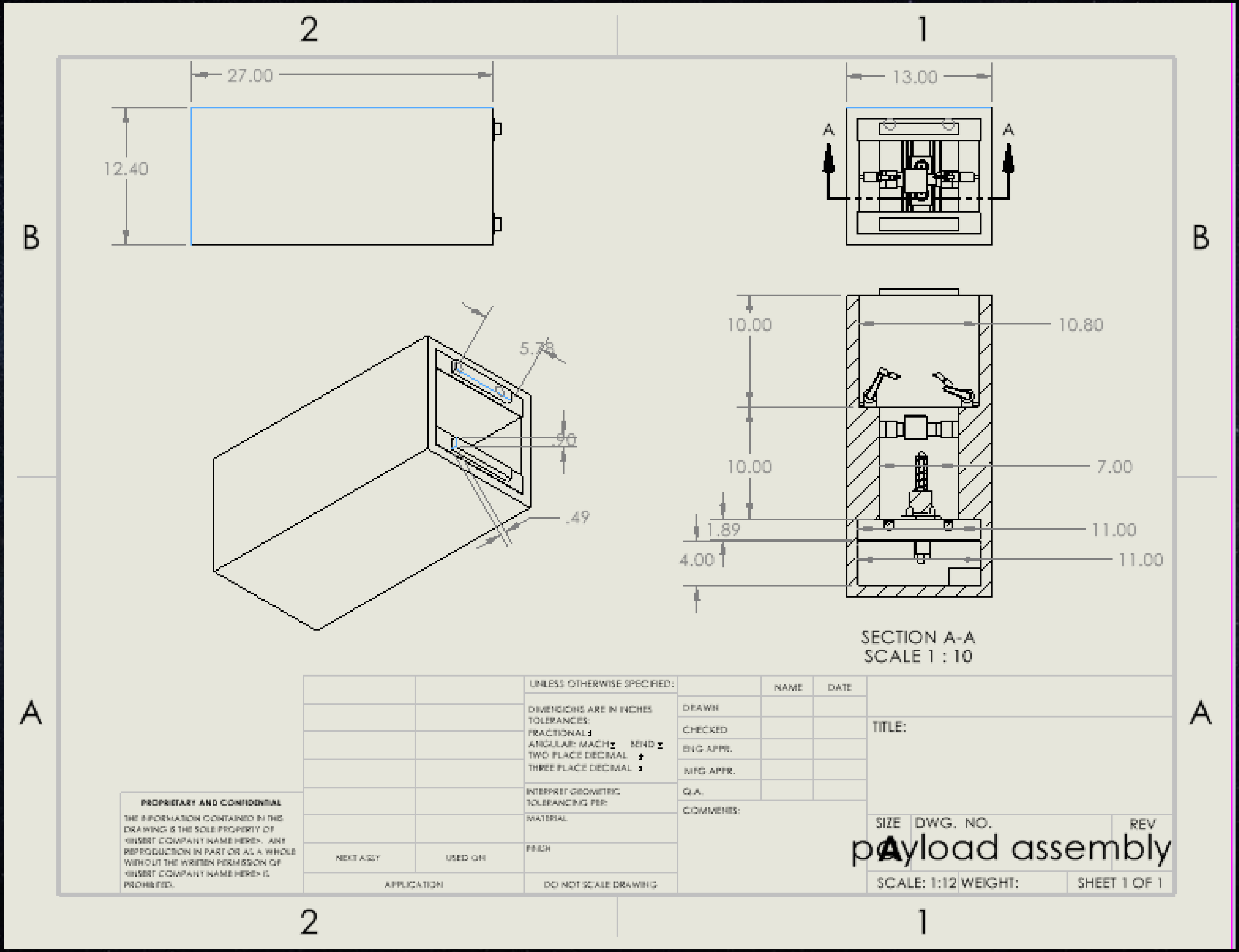
Demonstration of In-Space Coatings



Payload CAD Model

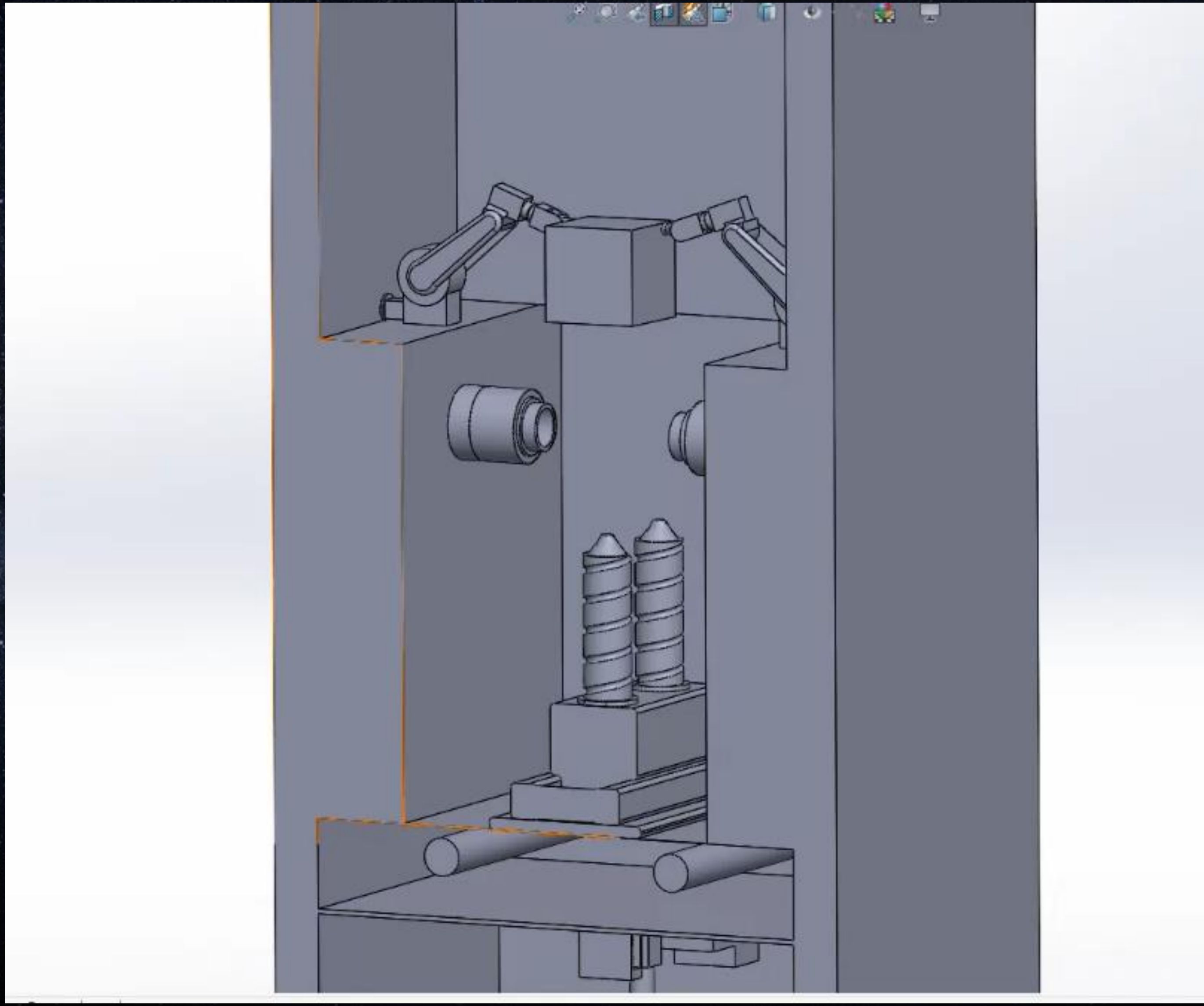
Demonstration of In-Space Coatings





2.1 Animation of Key Operating Sequence

Demonstration of In-Space Coatings



2.2 Operation (continued): Object Manipulation

Demonstration of In-Space Coatings

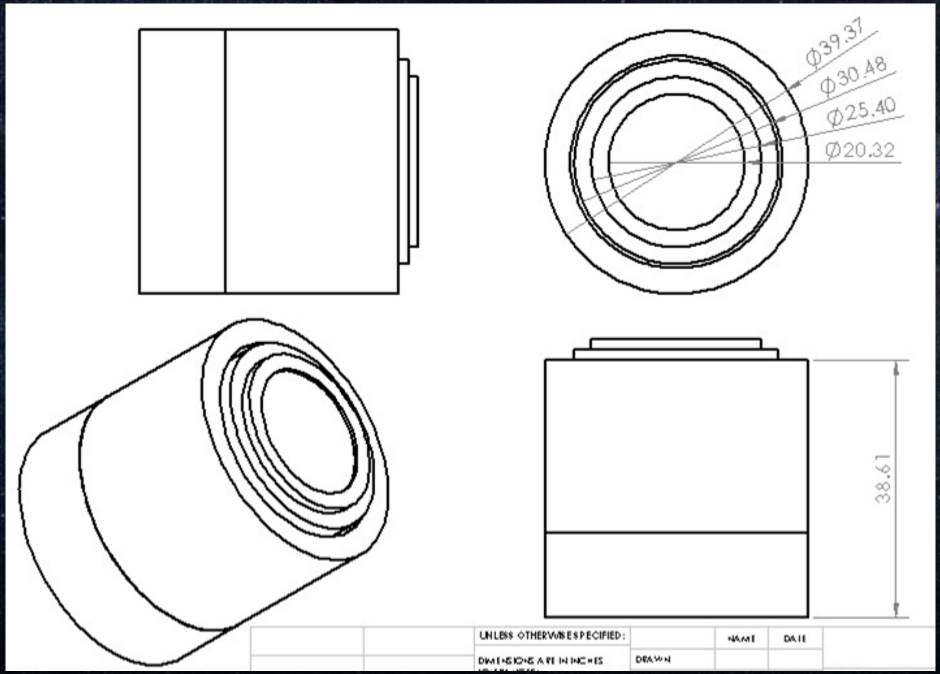
Operation 1: Grab onto objects to coat

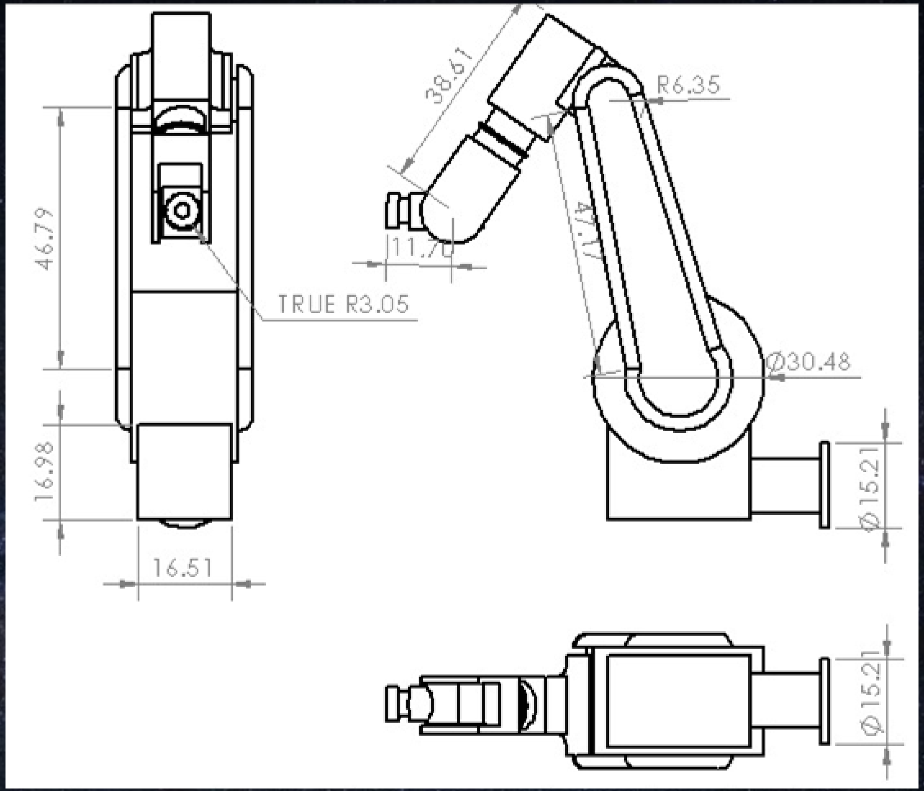
Robotic Arms:

- Mitsubishi RV-2AJ robot arm
- 5 degrees of freedom

Telescoping Arms:

- 2 degrees of freedom
- Active cooling





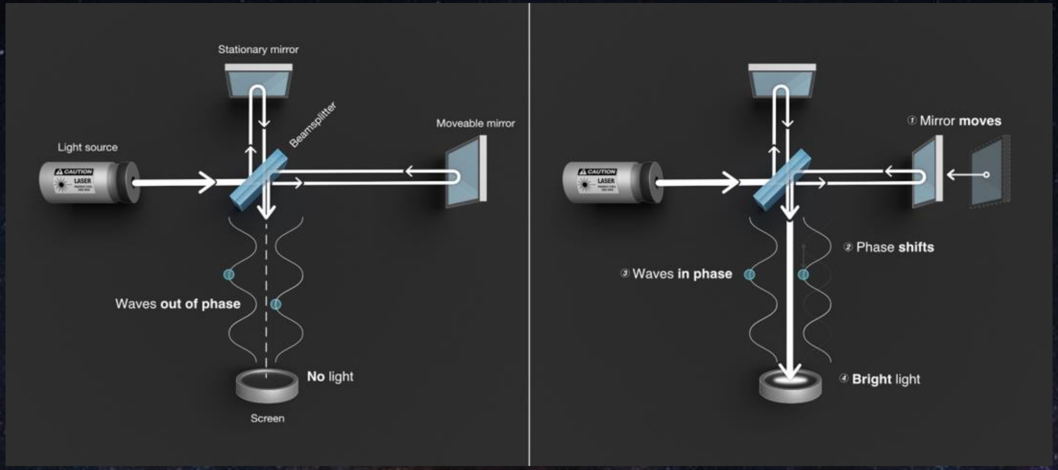
2.2 Operation (continued): Surface Characterization

Demonstration of In-Space Coatings

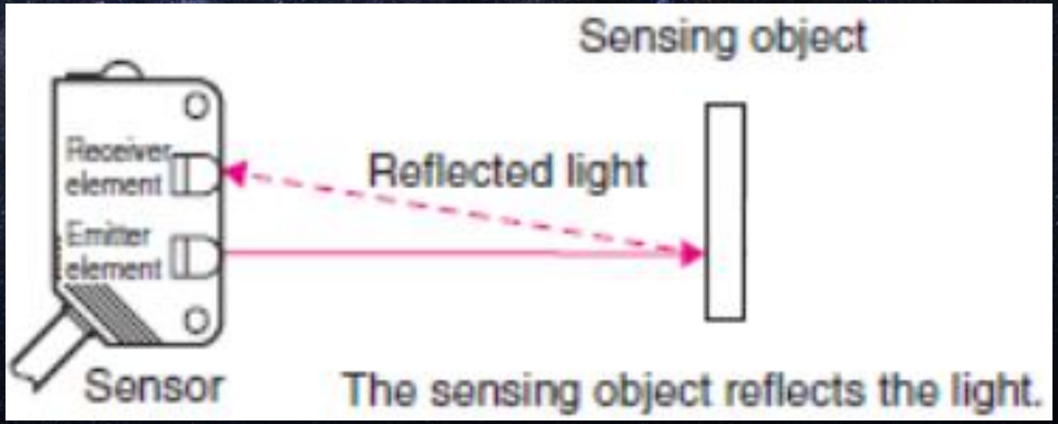
Operation 2: Analyze the surface both before and after coating to verify success

- Laser interferometer to measure the surface roughness
- White light emitter and receiver to measure reflectivity
- Camera with image recognition or possible human operation

Assumption: Already have data to compare the results to



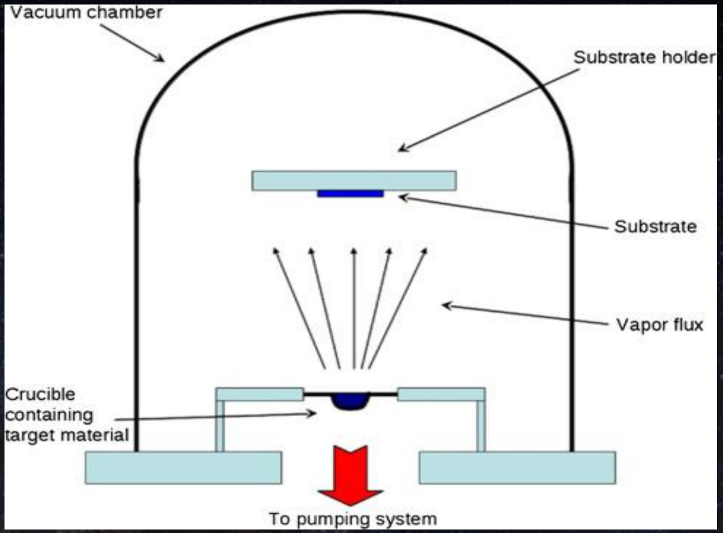
Simple Interferometer, nist.gov



Photoelectric Sensors, omron.com

2.2 Operation (continued): The Coating Process

Demonstration of In-Space Coatings



R.J. Martín-Palma, A. Lakhtakia, Vapor-deposition techniques, in: Engineered Biomimicry, 2013, pp. 383–398

Operation 3: Coat using the evaporation method

- Well-understand, mature, and simple technology

How it works:

- Material is placed inside the crucible which is heated with a coil
- Material then evaporates from the opening
- Both the substrate and the crucibles are moved to coat the entire surface evenly

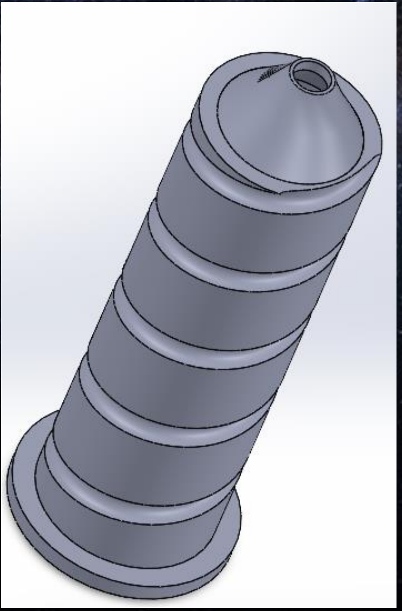
$$\frac{dN_e}{A_e\,dt} = \alpha_\nu (2\pi m k T)^{-1/2} (p^* - p)$$

$$\frac{t}{t_0} = \frac{1}{[1 + (x/h)^2]^2}$$

Vossen, J., Kern, W., (1991) “Thin Film Processes II”. https://doi.org/10.1016/B978-0-08-052421-4.50007-1

Design choices

- Crucibles made out of Boron Nitride or Vitreous Carbon
- Material is evaporated via resistive heating
- Spiral grooves for the coil to sit in



3.3 Biggest Challenges Encountered

Demonstration of In-Space Coatings

- Regulating the crucible temperature
- Generating the required power input to heat the crucible to desired temperature
  - Material heating estimated to require 400W
- Understanding the coating process under microgravity

Thermal Subsystem

Demonstration of In-Space Coatings

Heat shields

- Surrounding the crucible to minimize heat loss
  - Inner Shield: Molybdenum
  - Outer Shield: Yttria-Stabilized Zirconia

Space Copper-Water Heat Pipes

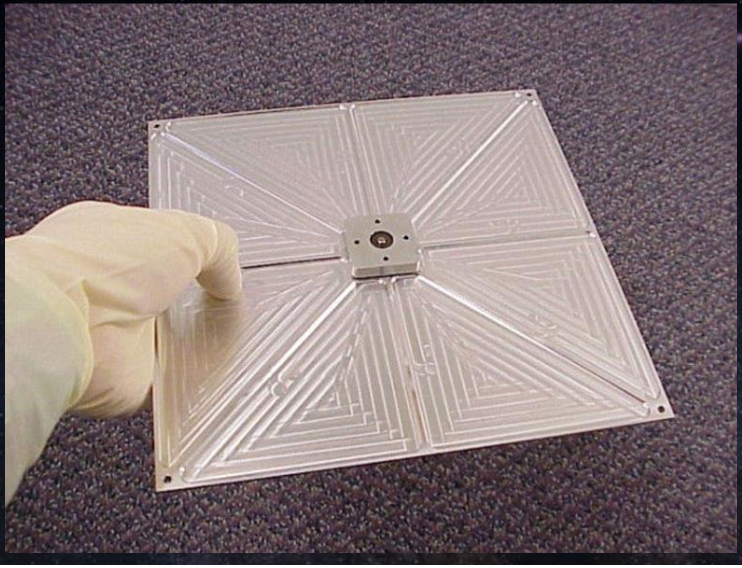
- Developed in conjunction with Advanced Cooling Technologies

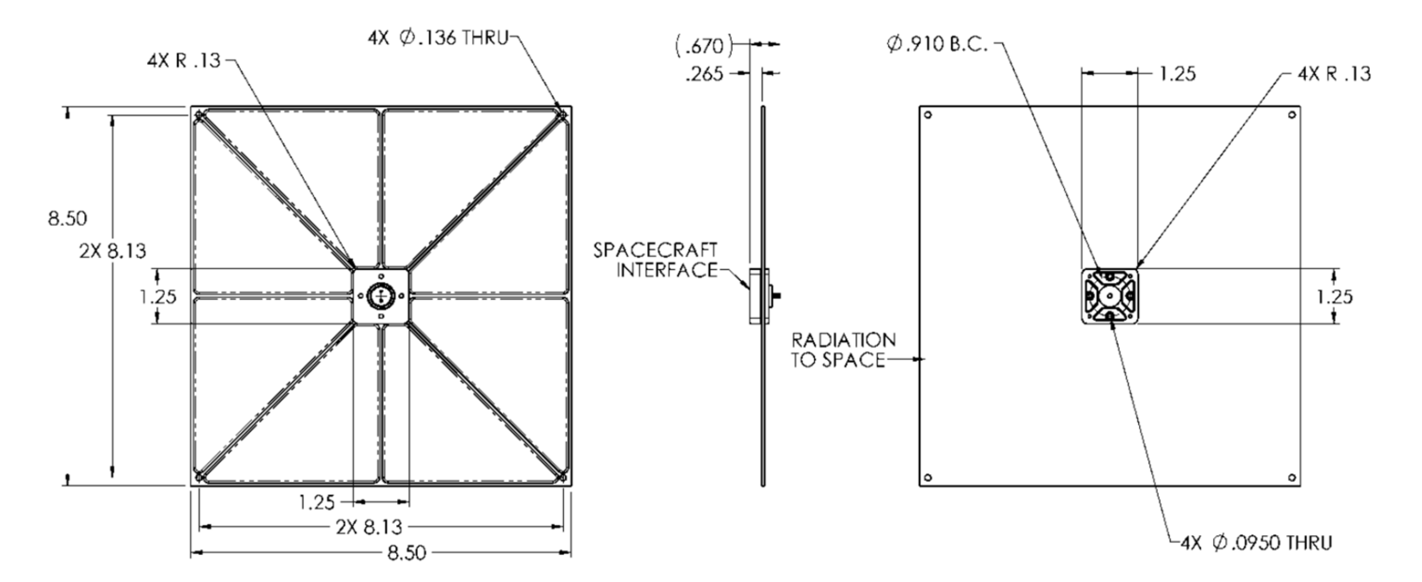
Radiators

- Dissipate excess heat into deep space

Other Thermal Technology

- Thermostats to monitor temperature
- Heaters and Coolers for small temperature fluctuations within secondary sections



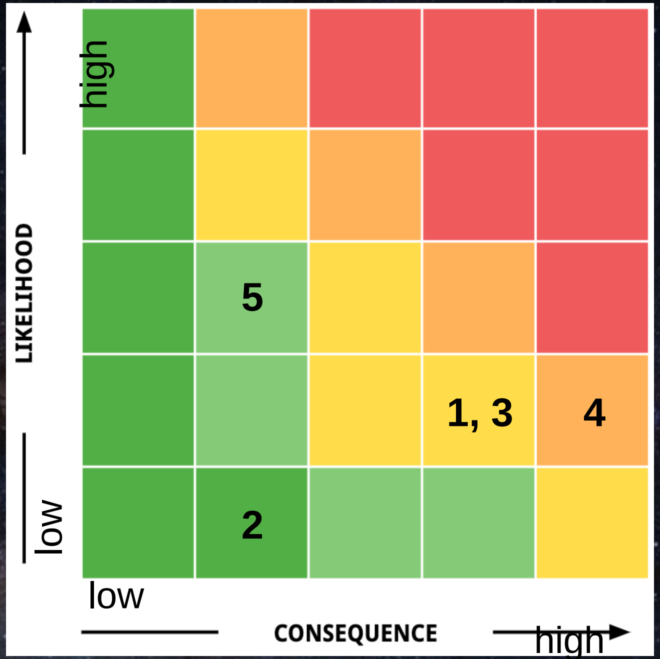


“Miniature satellite energy-regulating radiator (miser),” *Sierra Space Corporation*, Available: https://www.sierraspace.com/wp-content/uploads/2024/01/THERMAL-CONTROL-SYSTEMS-Miniature-Satellite-Energy-Regulating-Radiator-MiSER.pdf.

1.5 Risks

Demonstration of In-Space Coatings

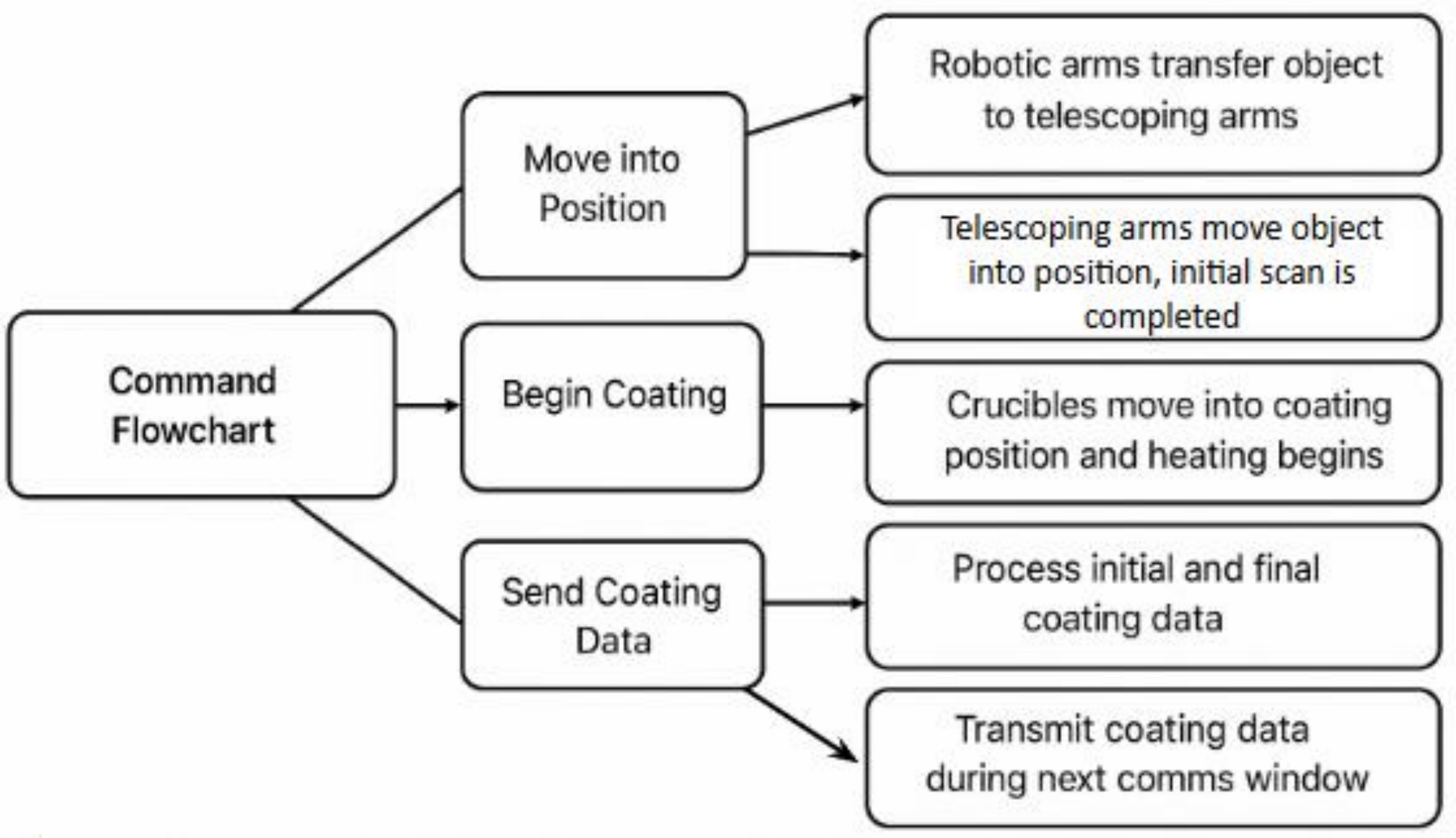
1. **Molten Metal Escape in Microgravity**: Free-floating molten metal inside the payload risks short-circuits or gumming up the moving parts
2. **Sensor Malfunction or Calibration Drift:** Sensors may become misaligned or drift over time
3. **Electronics Fail Due to Radiation Exposure:** Many components are COTS and not radiation-hardened
4. **Crucible Heating Element Burnout:** Power cycling could degrade the resistive coil, halting coating operations prematurely
5. **Damage of the target substrate:** Heat radiated from the crucible and conducted by gaseous particles might damage the substrate



2.3 Data Handling and Comms

Demonstration of In-Space Coatings

- Amazon Web Services (AWS)
  - Tons of global locations, great for orbit evolution
- Do not need constant downlink
  - 3.5 Mbps bitrate
  - Sending photos, coating data, telemetry
  - Link Margin = 25.07 dB
- 1.5 Mbps uplink bitrate
  - Only sending commands
  - Link Margin = 22.46 dB
- Antelope Computer
  - 8gb DDR4 RAM, 4-8 gb flash storage



1.6 Path to PDR: Bus Integration

Demonstration of In-Space Coatings

- Proposed X-Class bus components
- Attitude Control System - Flex Core
  - Pointing accuracy and error
- Star Tracker - Standard
- Reaction Wheels - RW8
  - Highest torque
  - Lowest power requirements
- Antenna - S/X Band All Metal Patch
  - right operating frequency for AWS
- Thermal - Standard
  - Payload designed to dissipate heat before reaching the bus

SatCatalog, “X-sat venus class,” *SatCatalog* Available: https://www.satcatalog.com/component/x-sat-venus-class/.

1.6 Path to PDR (Continued): Secondary Power Supply

Battery Name, Company	Weight	Goal	43 Ah, EaglePicher	60 Ah, EaglePicher	28-Volt Modular, Ibeos	SmallSat, Ibeos
Capacity (Ah)	0.05	MAX	43.00	60.00	29.46	5.08
Normalized value			0.69	1.00	0.44	0.00
Storage (Wh)	0.20	MAX	154.80	216.00	825.00	135.00
Normalized value			0.03	0.12	1.00	0.00
Max Discharge Rate (A)	0.40	MAX	200.00	250.00	60.00	10.00
Normalized value			0.79	1.00	0.21	0.00
Max Charge Rate (A)	0.10	MAX	21.50	12.00	15.00	2.50
Normalized value			1.00	0.50	0.66	0.00
Volume (cm^3)	0.15	MIN	897.07	1,514.23	4630.50	418.40
Normalized value			0.89	0.74	0.00	1.00
Mass (kg)	0.05	MIN	1.27	1.60	5.90	0.82
Normalized value			0.91	0.85	0.00	1.00
Temperature Range (deg C)	0.05	MAX	80.00	60.00	45.00	45.00
Normalized value			1.00	0.43	0.00	0.00
Totals:	1.00		0.69	0.70	0.37	0.20

1.6 Path to PDR (Continued): Power Budget

Subsystem	Peak Power Consumption (Coating Inactive) (W)	Peak Power Consumption (Coating Active) (W)
Evaporation Coating	0.0	415.0
Propulsion	0.0	0.0
Thermal	22.2	22.2
Structures	0.0	0.0
Power	4.9	4.9
CD&H, Uplink, & Downlink	14.0	14.0
Attitude Control	23.5	0.0
System Reserve (20%)	88.8	238.8
Battery Charging	290.6	0.0
Total Power Used	**444.0**	**694.9**
Solar Panel Power Generation	444.0	444.0
Battery Power Generation	0.0	750.0
Total Power Generation	**444.0**	**1194.0**

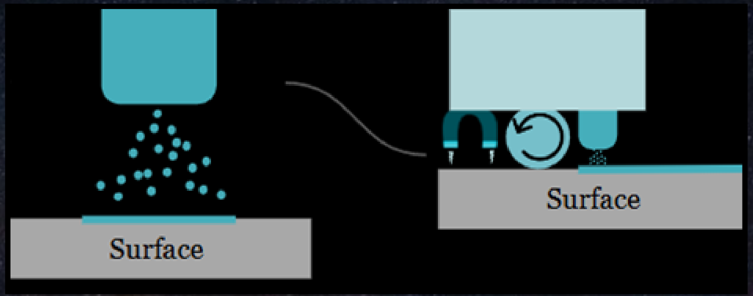
1.6 Path to PDR (Continued): Mass Budget

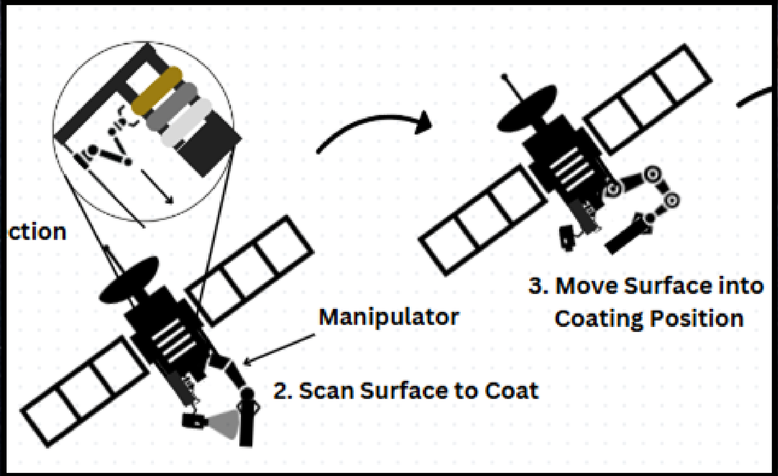
Subsystem	Component(s)	Estimated Mass (kg)
Structures	Aluminum 7075 frame and support lattice	21.0
Coating Process	Crucibles, robotic arms, telescoping arms, slider	16.5
Thermal System	Heat pipes, radiators, heat shields, insulation	5.0
Surface Characterization	Camera, laser interferometer, photodiode sensor	3.0
Command & Data Handling	KP Labs Antelope OBC, cabling, sensors interface	1.5
Power Subsystem	Li-ion batteries, harnesses	2.0
Mounting Hardware	Bolts, brackets, fasteners	1.0
Contingency Margin	(15% of subtotal above)	7.6
Total Estimated Payload Mass		**57.6**

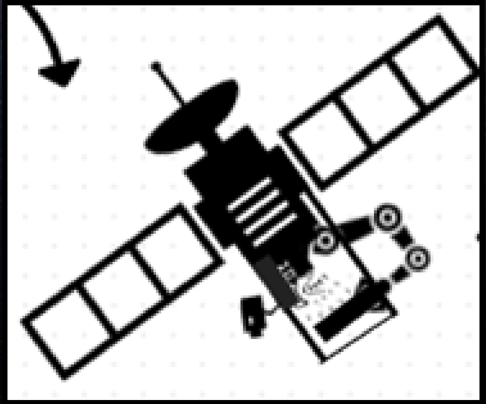
3.1 Innovative Concepts

Demonstration of In-Space Coatings

- **External Coating**
  - Attach to the outside of a large object (e.g. a satellite)
  - Coat the entire outside by rolling along the outer surface
- **Hybrid Method**
  - Grabs medium-sized objects with a robotic arm
  - Deploys a protective cowling around the entire object before beginning coating
- **Internal Coating**
  - Intake small objects to be coated
  - Use small robotic arms to move the part to coat the entire surface







Space Coatings

3.2 Technology Gap Assessment

Demonstration of In-Space Coatings

- **Thermal Management for Internal High-Temp Systems in Small Payloads**
  Managing 2200°C+ processes within compact volumes without harming sensitive electronics is an unproven capability in space hardware.

- **No Coating Process Integration with Future ISAM Workflows**
  There is no precedent for integrating coating systems into future autonomous manufacturing and assembly operations in orbit.

- **No Proven Method for Handling Molten Materials in Microgravity**
  Current evaporation methods depend on gravity to contain and direct molten material. Space-compatible containment and flow control has not been validated.

4.1 Paper

Demonstration of In-Space Coatings

- Goes into greater detail about the coating process
- Abstract length: 201 words
- Paper length: 20 pages
- 22 references
- Planned publications
  - AIAA SciTech Conference, Jan 12-16 2026 Orlando, FL

1.6 Path to PDR (continued): Future Work

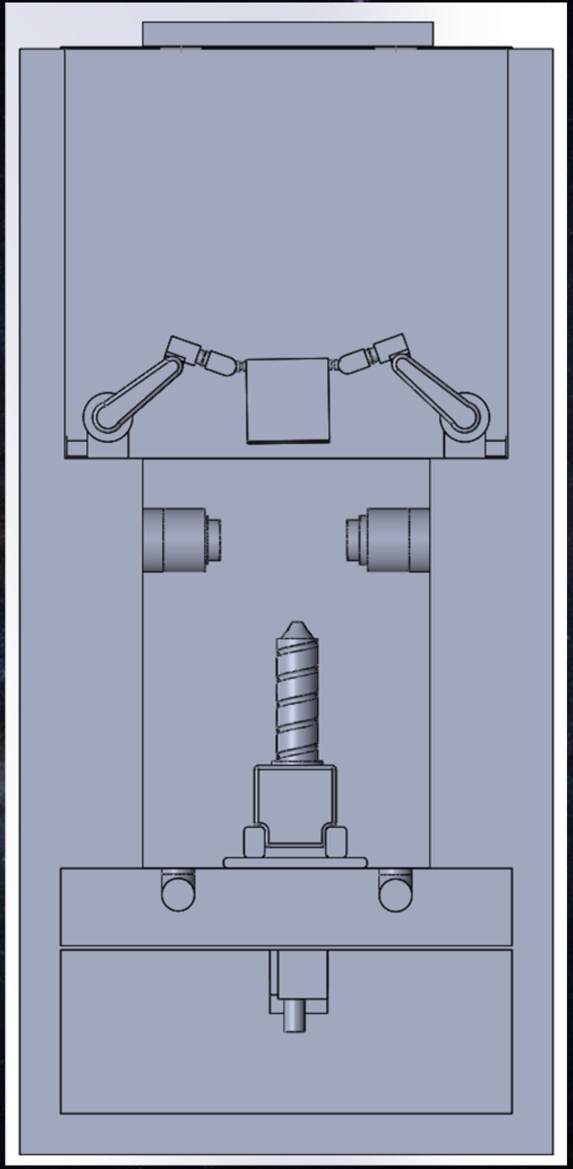
Demonstration of In-Space Coatings

- Consider other bus' with higher power capabilities
  - larger size to reduce risks associated with heat
- On ground testing of Antelope computer for a coating application with sensors, camera, etc
- Rideshare onboard SpaceX Falcon 9
  - full vibrational launch testing
- Work with BCT for full integration
- More robust mechanical arms to coat complex shapes
- Work with commercial suppliers to create more mission-specific components
- Test electronics and sensors on ground for coating applications

Summary/ Conclusion/ Highlights

Demonstration of In-Space Coatings

- In-Space coating is a key enabling technology for future ISAM capabilities:
  - Possibility to integrate into an assembly line
  - Objects that are made in space need to be made space-resistant
  - Thin film coatings generated in the vacuum of space are better
  - Coatings that are damaged or degraded need to be serviced
  - Possible Sci-Fi technology (e.g. solar sails*, fission sails)
- Lessons learned:
  - Use commercially available parts instead of designing from scratch
  - Have a coatings expert more closely involved in the project
  - Interdependency of subsystems



* Lippman, M. E. (1972). "In-Space Fabrication of Thin-Film Structures" Astro Research Corporation. ntrs.nasa.gov/api/citations/19720009888/downloads/19720009888.pdf

Questions

Demonstration of In-Space Coatings

Questions?

Backup Slides

Thermal Subsystem

A Deeper Dive into the Thermal Design of the Payload

Challenge:

- Dissipate the 9627.04 Watts of energy produced by the heating of the crucible at 1650 C

Solution:

- Heat shields
  - Surrounding the crucible to minimize heat loss
    - Inner Shield: Molybdenum
    - Outer Shield: Yttria-Stabilized Zirconia
- Heat pipes
  - Developed in conjunction with Advanced Cooling Technologies
- Radiators
  - Dissipate excess heat into deep space
- Thermostats, heaters, and coolers for small temperature fluctuations within secondary sections

Subsystem Lead: Noah Smargiassi

Thermal Subsystem

Heat Shields

Primary Goal:

- Minimize heat loss by reflecting heat back into the crucible
- Spaced apart for a vacuum gap allowing heat transfer only through radiation
- $Q = \varepsilon * \sigma * A * T^4$

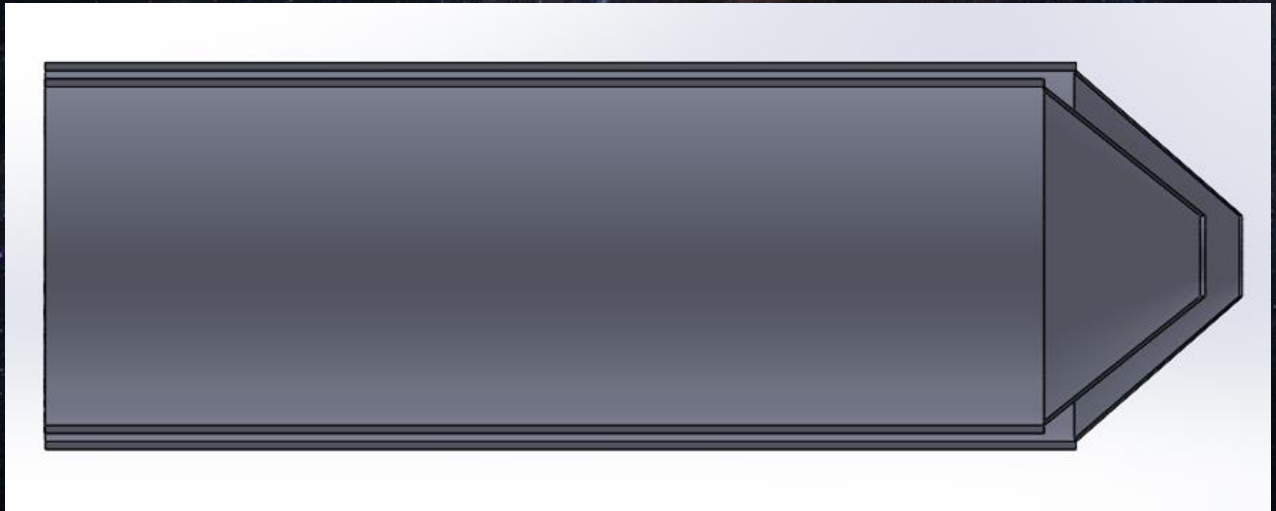
Inner Shield: Molybdenum

- Emissivity at 1650 C: 0.205

Outer Shield: Yttria-Stabilized Zirconia

- Emissivity at 1650 C: 0.238

Q emitted through heat shields: ~400 W



Subsystem Lead: Noah Smargiassi

Thermal Subsystem

Heat Pipes and Radiators

Primary Goal:

- Dissipate the excess heat emitted through the heat shields
- Protect electronics and other devices within payload secondary areas

Excess Heat: ~400 W

Heat Pipes:

- Space Copper-Water Heat Pipes
  - High Heat Flux Capacity: 50 W/cm^2
- Developed in conjunction with Advanced Cooling Technologies to meet specific payload requirements

Radiators:

- Developed in conjunction with Sierra Space to meet specific payload requirements

Subsystem Lead: Noah Smargiassi

Thermal Subsystem

Other Thermal Technology

Temperature Monitoring: Sensata Technologies M2 Series Space Flight Thermostats

- Located within the hallways and electrical box to monitor temperature
- Temperatures in these areas must remain between -10 C and 50 C

Heaters: Developed in conjunction with Minco for specific payload requirements

- Located within the hallways and electrical box to regulate temperature
- If temperature drops below -10 C, the heater automatically activates until desired range is reached

Coolers: Developed in conjunction with Dynavac for specific payload requirements

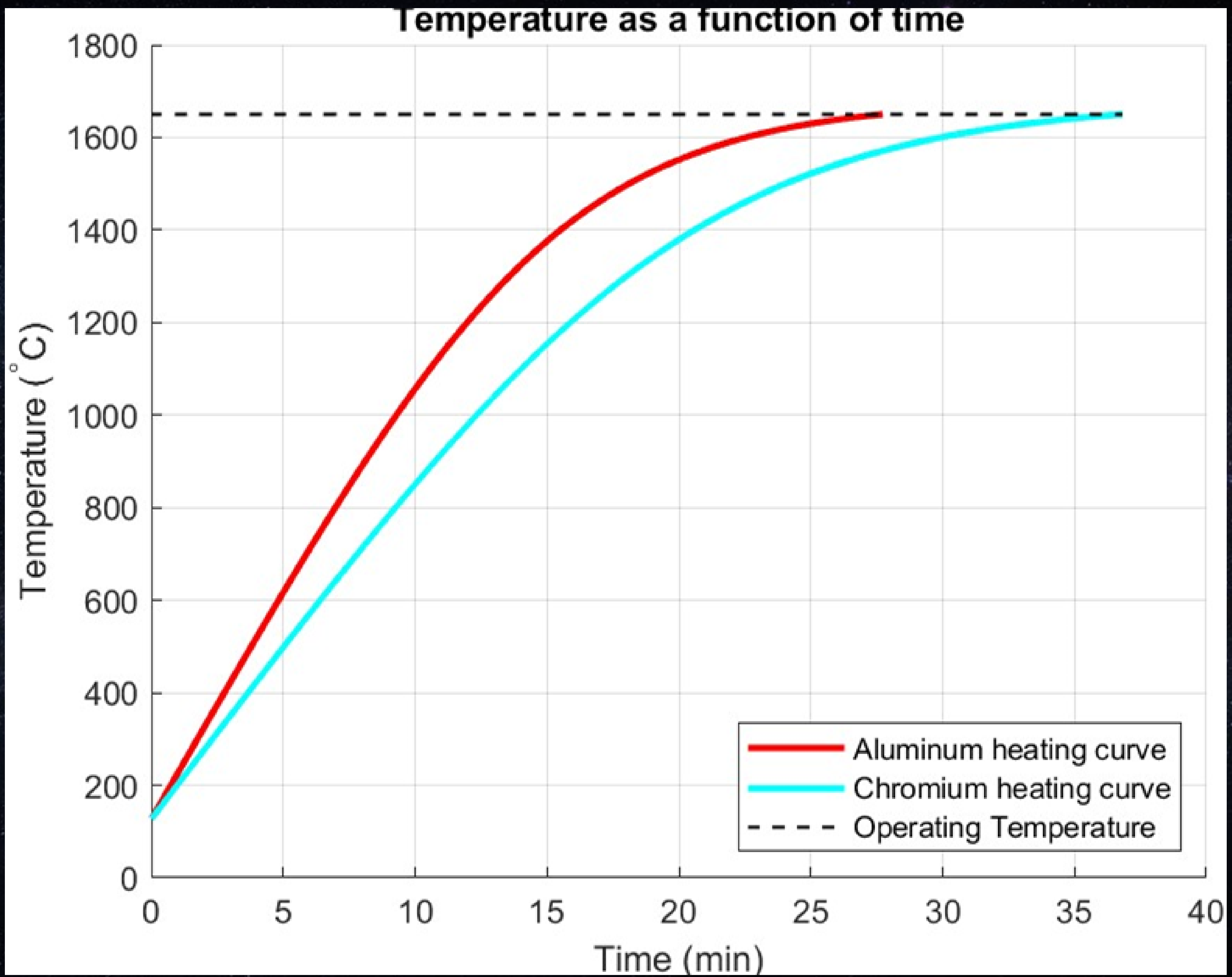
- Located within the hallways and electrical box to regulate temperature
- If temperature reaches above 50 C, cooler activates until desired range is reached

Subsystem Lead: Noah Smargiassi

Thermal Subsystem

Heating Profile

- Input power = 415 W during ramp up
- Heating times
  - Aluminum: 1665 seconds = 28 minutes
  - Chromium: 2210 seconds = 37 minutes



Power Subsystem

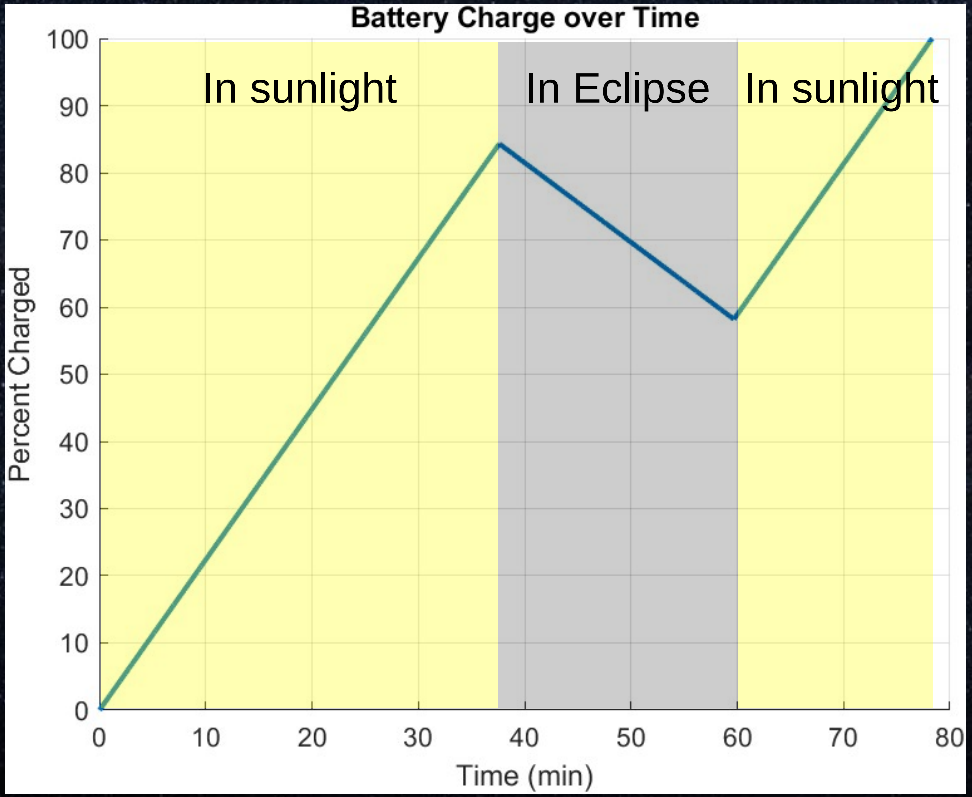
Selection of Secondary Battery Type

Performance Characteristic	Ni-Cd	Ni-H2	Li-ion
Energy Density (W*hr/kg)	30	60	125
Energy Efficiency (%)	72	70	98
Thermal Power (scale 1-10)	8	10	1
Self-Discharge (% per day)	1	10	0.3
Temperature Range (C)	0-40	-20-30	10-25
Memory Effect	Yes	Yes	No
Energy Gauge	No	Pressure	Voltage
Trickle Charge	Yes	Yes	No
Modularity	No	No	Yes
Heritage	Yes	Yes	Yes

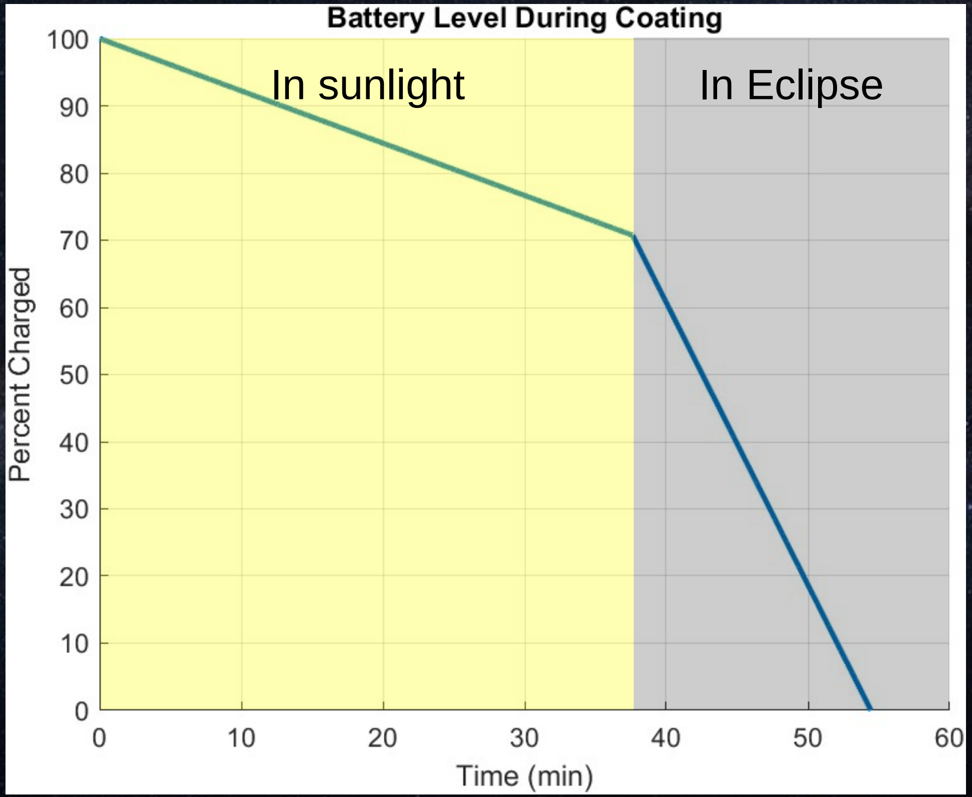
Power Subsystem

Power profile of the battery

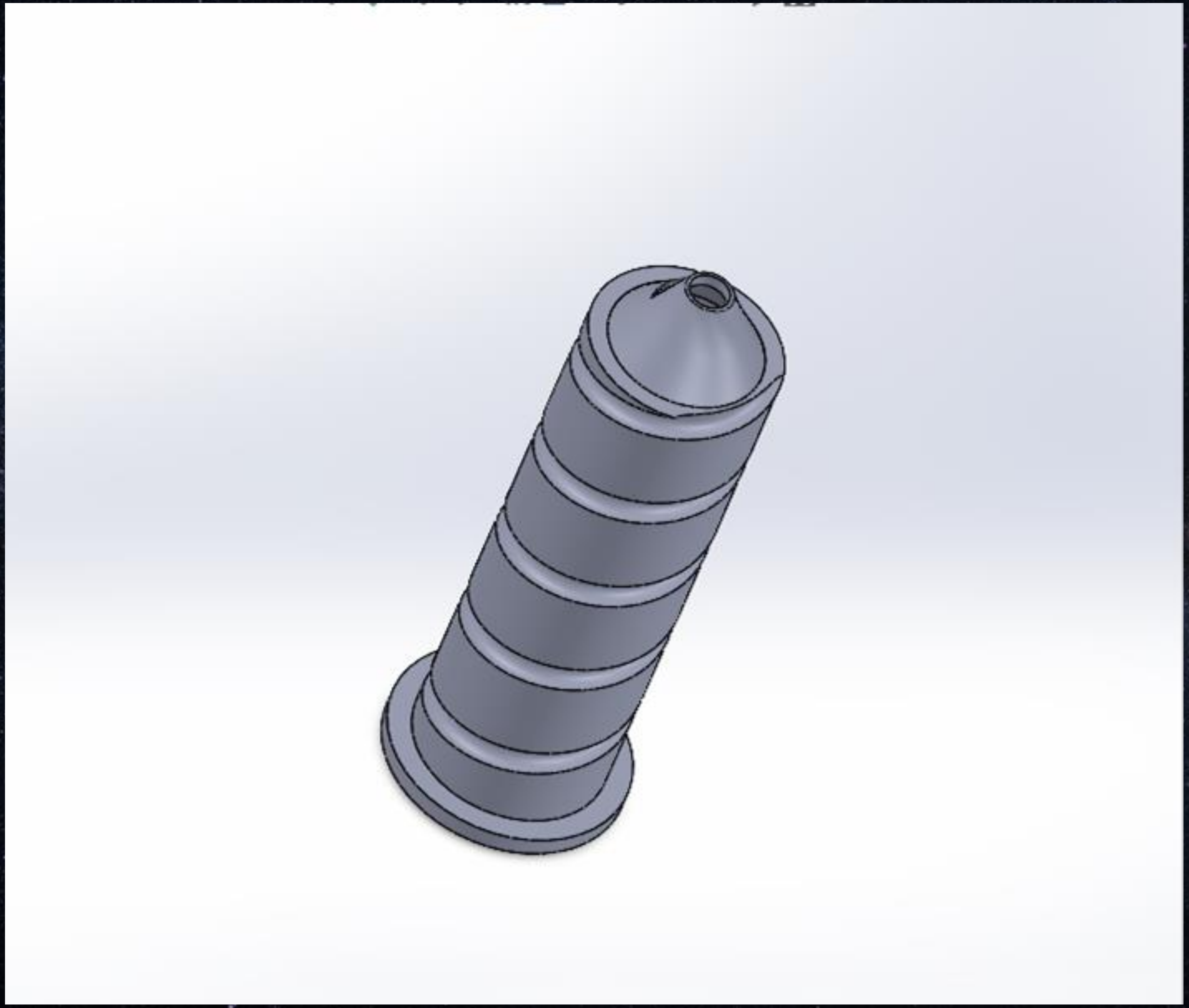
Given a surplus of 290.6W when the coating system is inactive, it takes more than 1 orbit to fully charge the battery

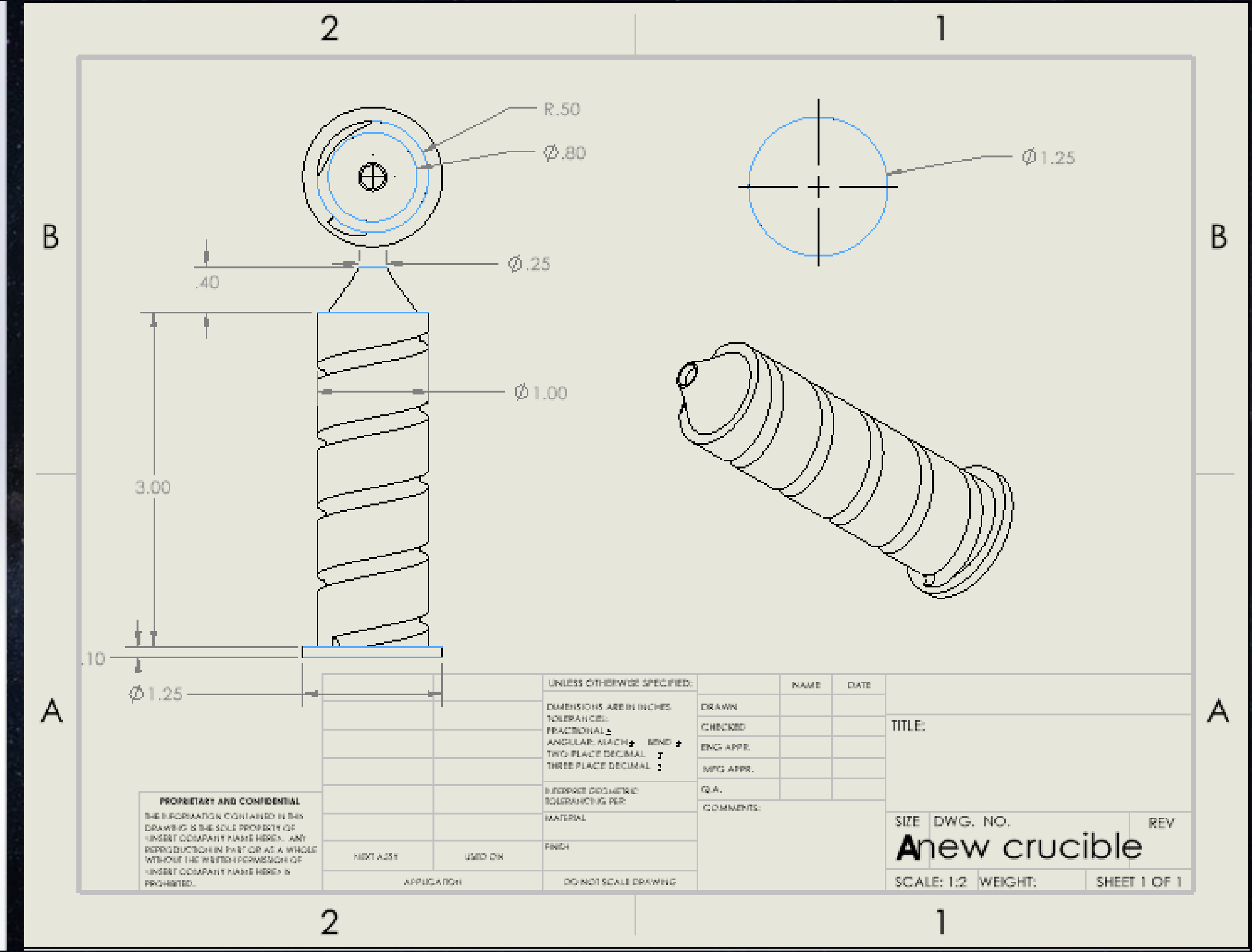


With a fully charged battery + solar power, the coating system can run continuously for 54 minutes



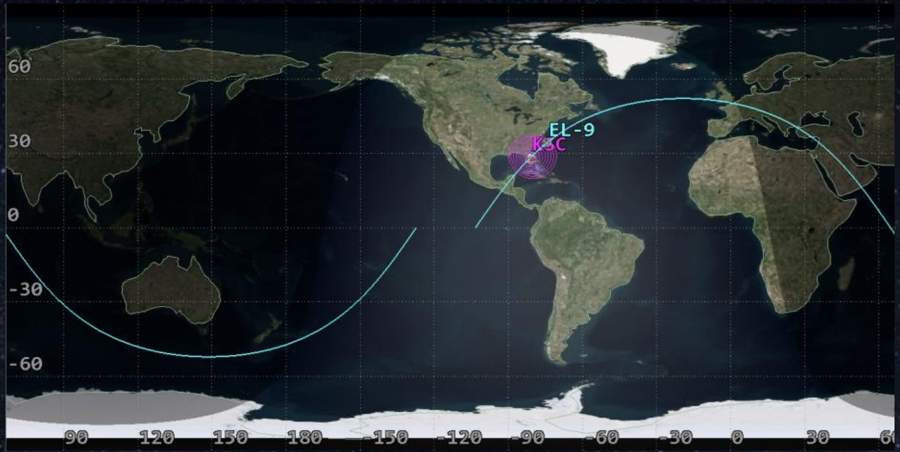
Crucible CAD Model

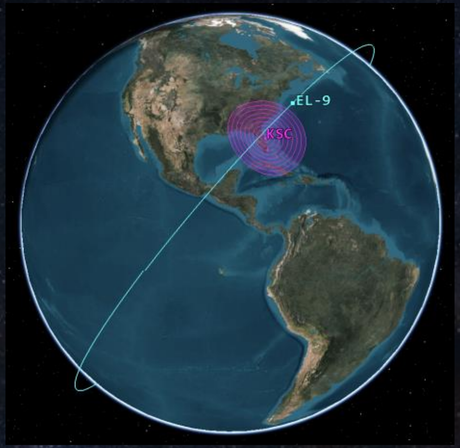




Astrodynamics Subsystem

Mission Orbital Parameters



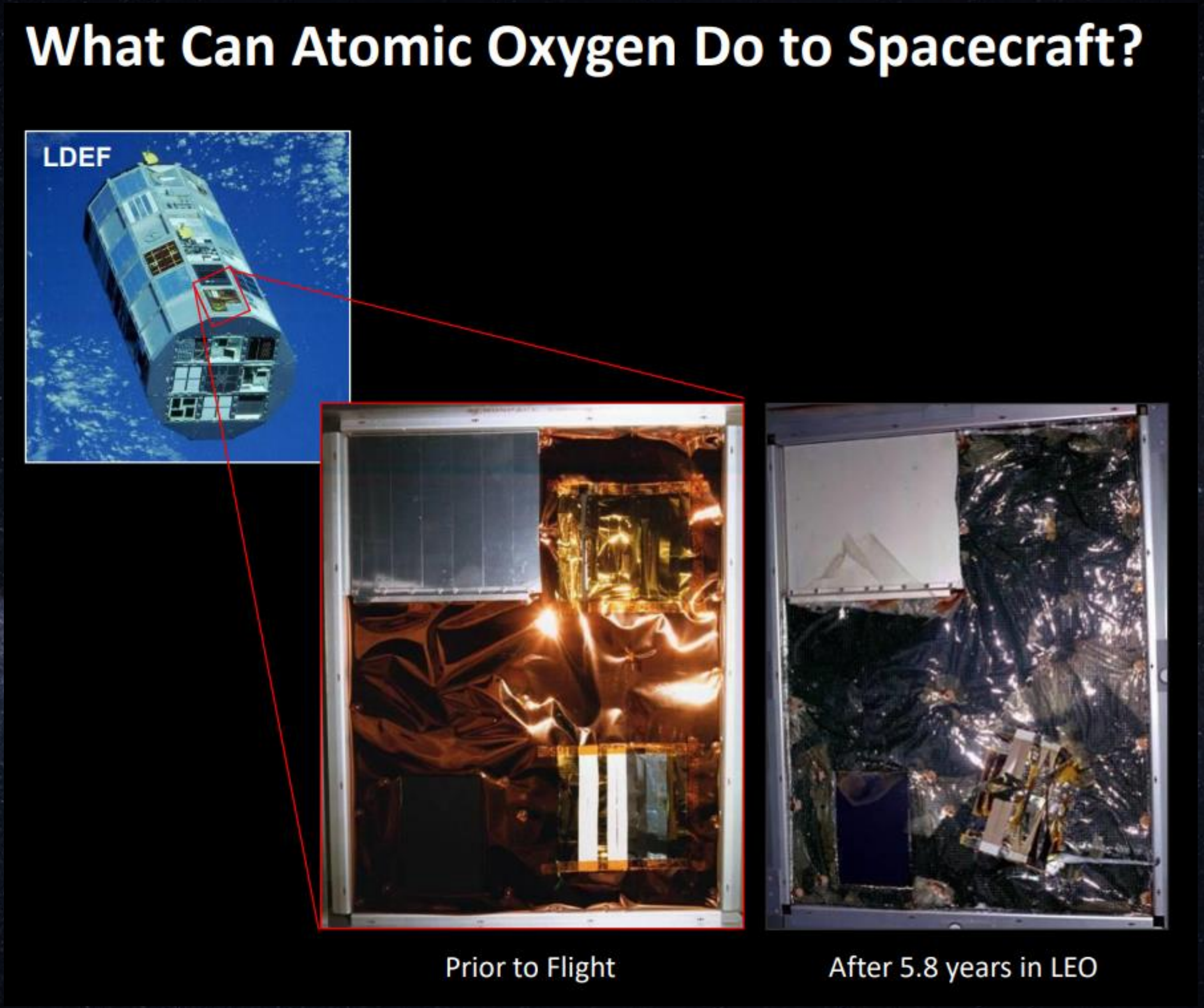


Property	Value	Justification
Orbit Type	Circular	Simplification of a standard LEO for ease of calculations
Altitude	500 km	Roughly halfway between the altitudes of the ISS and Starlink
Inclination	52 degrees	Roughly the same inclination as the ISS (51.6 degrees)
Launch Site	Kennedy Space Center	Capable of launching directly into the desired inclination
Sunlight Time	63.35% of each orbit	Realistic orbit that satellites operate at

Subsystem Lead: Kaiden Smith

Material Degradation in LEO

- NASA's Long Duration Exposure Facility (LDEF)
  - Effects of atomic oxygen
  - Micro-meteoroids & space debris
- This highlights the need for coatings servicing



Miller, S., "Coatings and Surface Treatments for Space Applications", NASA Glenn Research Center, June 2023

Other Uses for Coatings

- Scientific Instruments (e.g. telescope mirrors)
- Microelectronics manufacturing

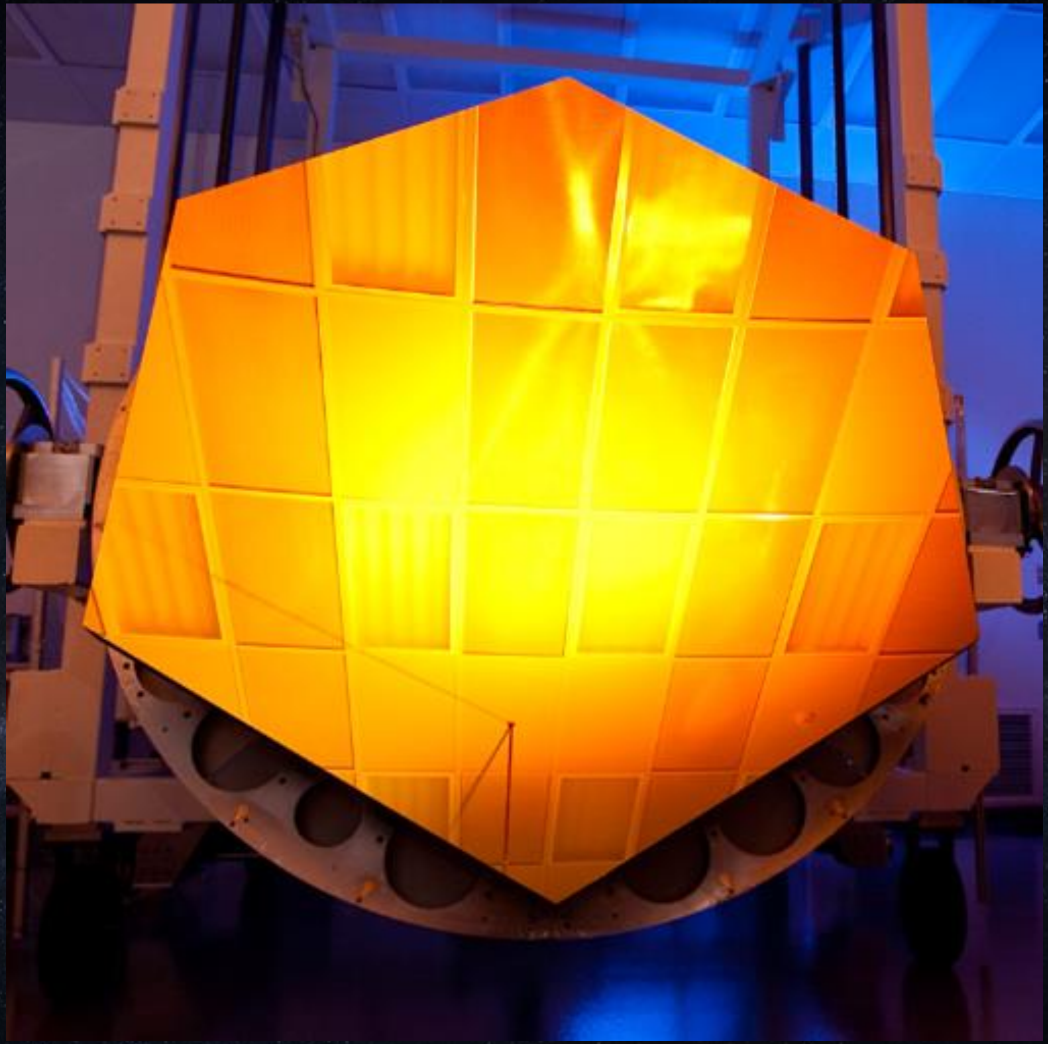


Image of a JWST mirror that reflects infrared using a coating that is 10^{-7} m thick

Noel, D. (2010, June 25). [Gold-coated Engineering Design Unit (EDU) Primary Mirror Segment]. Flickr. https://flic.kr/p/8jWHvM

Coating Subsystem

Material properties of the coating

Nestell, J. E., Christy, R. W., Cohen, M. H., Ruben, G. C. (1980). “Structure and optical properties of evaporated films of the Cr- and V-group metals”. *Journal of Applied Physics*. doi-org.ezaccess.libraries.psu.edu/10.1063/1.327321

- Crystal structure of chromium from the evaporation method is BCC (Body-Centered Cubic). This is the same crystal structure as regular chromium
- Smaller grain sizes from the evaporation method, leading to better material properties
  - Higher yield strength
  - Higher fatigue strength
  - Higher fracture toughness

Coating Subsystem

Material properties of the coating

Jankowski, A., Hayes, J. (2004). “The evaporative deposition of aluminum coatings and shapes with grain size control”. *Thin Solid Films*. https://doi.org/10.1016/j.tsf.2003.07.018

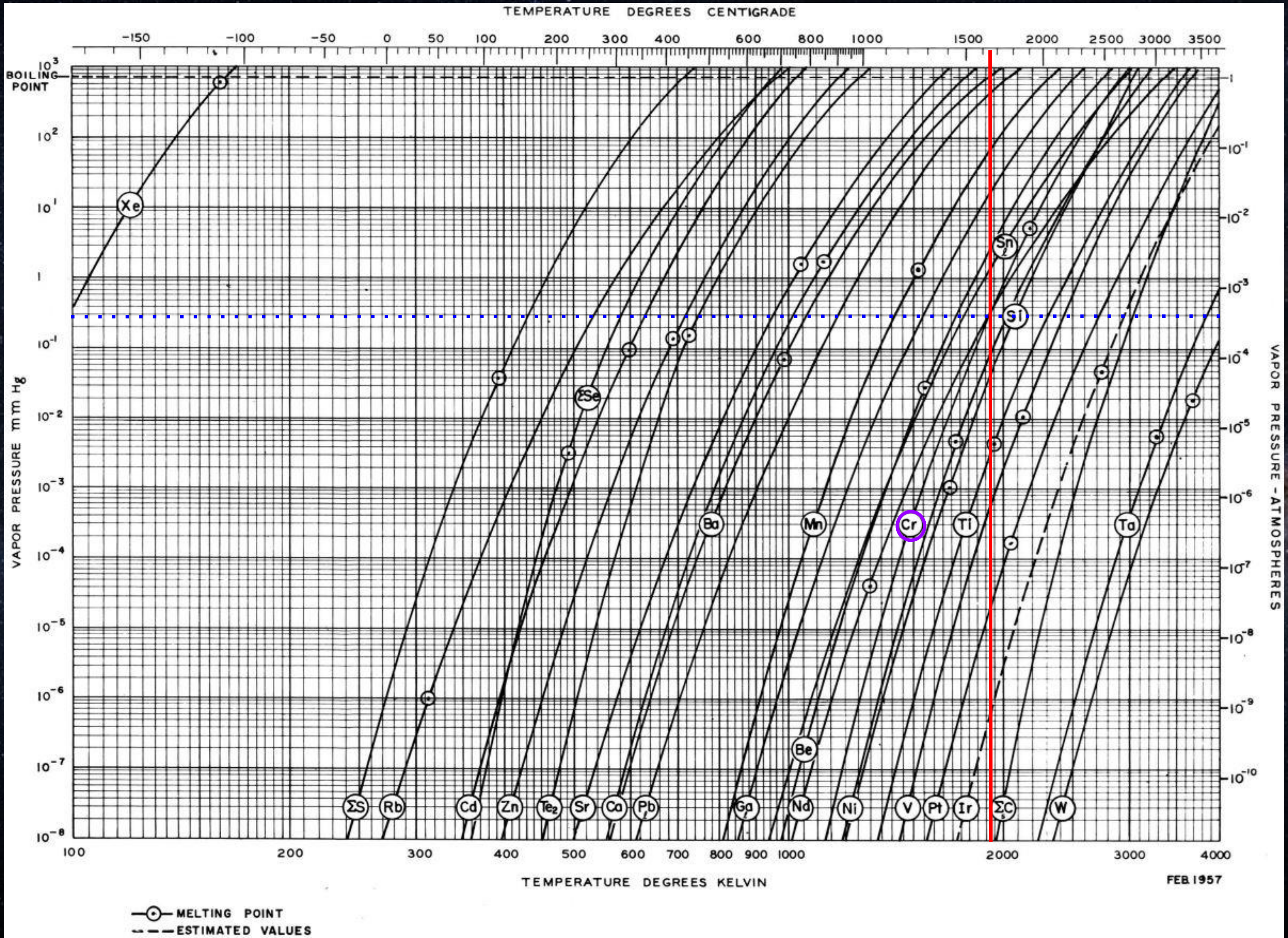
- Crystal structure of aluminum from the evaporation method is FCC (Face-Centered Cubic). This is its normal crystal structure
- Smaller grain sizes from the evaporation method, leading to better material properties
  - Higher yield strength
  - Higher fatigue strength
  - Higher fracture toughness

Table 1. Grain size control in aluminum coatings on mica

Sample no.	i (mA)	r (nm·s^{-1})	t_c (μm)	T_s (°C)	T_c (°C)	d_g (μm)
1113	0.38	1.0	22	204±13	264±12	5.4±0.7
1121	0.50	5.3	34	321±16	340±26	32±2
716	0.56	77.5	79	419±5	414±10	81±4
731	0.56	98.0	100	470±18	459±5	128±9
923	0.44	29.8	34	542±12	502±13	817±151
920	0.44	23.8	34	601±11	535±12	>2900

Coating Subsystem

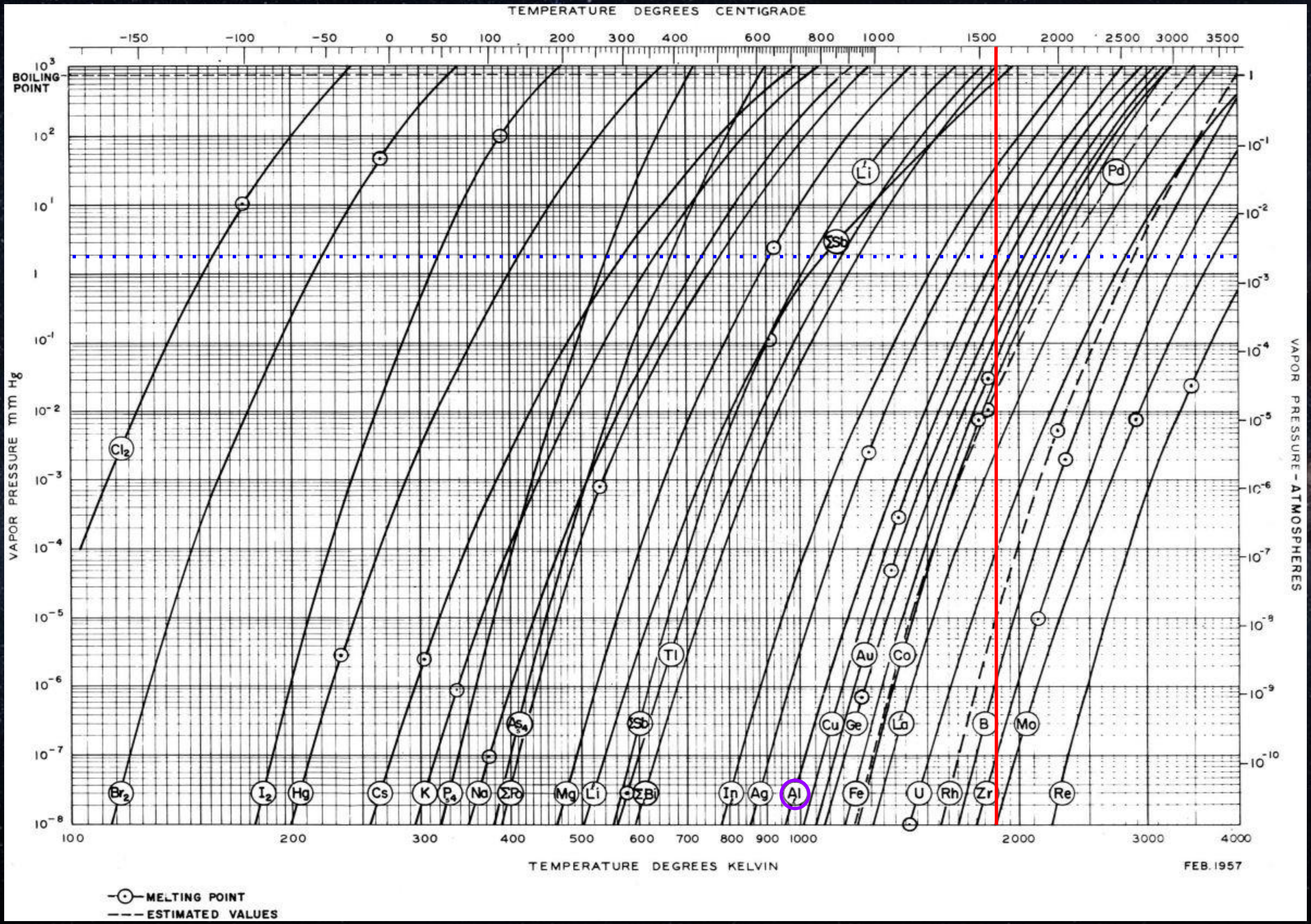
Vapor Pressures as a Function of Temperature (Continued)



"Vapor Pressure Data for the More Common Elements" (1957), RCA Laboratories, https://www.one-electron.com/Archives/RCA/RCA-RB/RB-104%20RCA%20Labs%201957%20Vapor%20Pressure%20Data%20for%20the%20More%20Common%20Elements.pdf

Coating Subsystem

Vapor Pressures as a Function of Temperature (Continued)



"Vapor Pressure Data for the More Common Elements" (1957), RCA Laboratories, https://www.one-electron.com/Archives/RCA/RCA-RB/RB-104%20RCA%20Labs%201957%20Vapor%20Pressure%20Data%20for%20the%20More%20Common%20Elements.pdf

Coating Subsystem

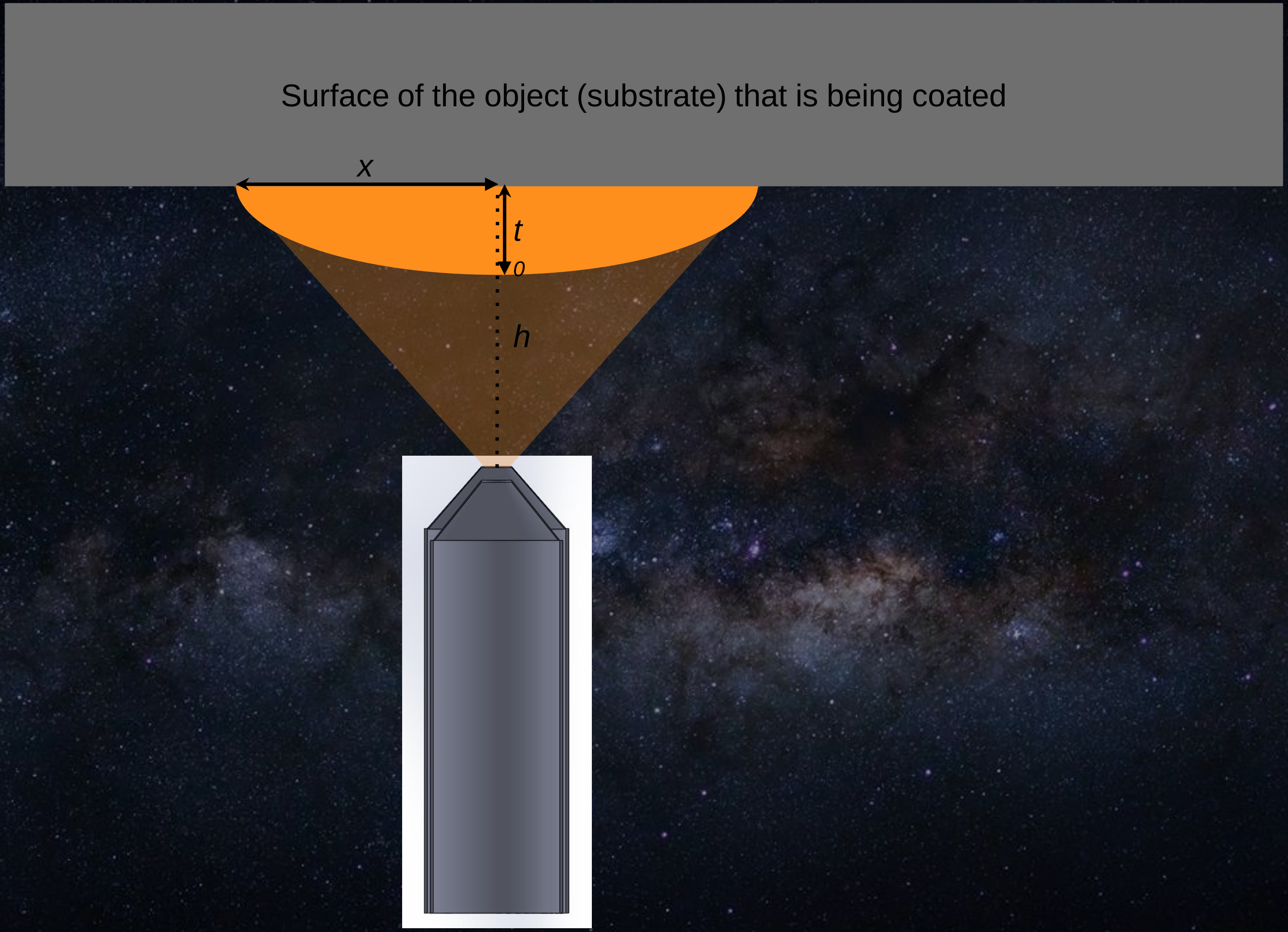
Thickness Distribution

The thickness is governed by the Knudsen cosine law:

$$\frac{t}{t_0} = \frac{1}{[(1 + x/h)^2]^{3/2}}$$

Distance from substrate, *h* = 2.54 cm

Location of next pass: 1.64 cm away in order to manufacture a smooth coating



Coating Subsystem

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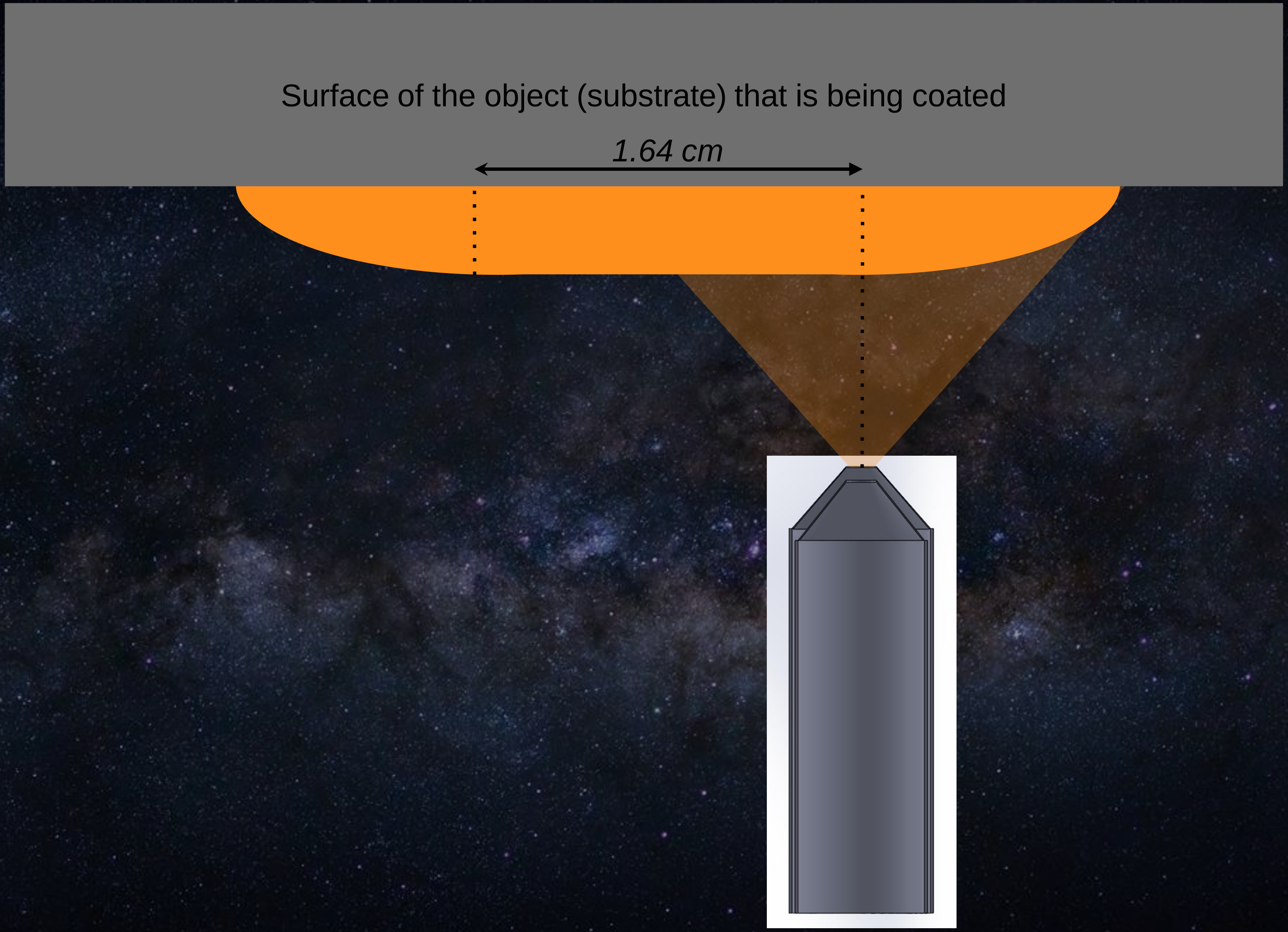


Coating Subsystem

Decision Matrix for Material Choices

- The following are the decision matrices used for choosing the materials to coat with
- Values are normalized to largest within their respective column
- The weighting for each category is also provided

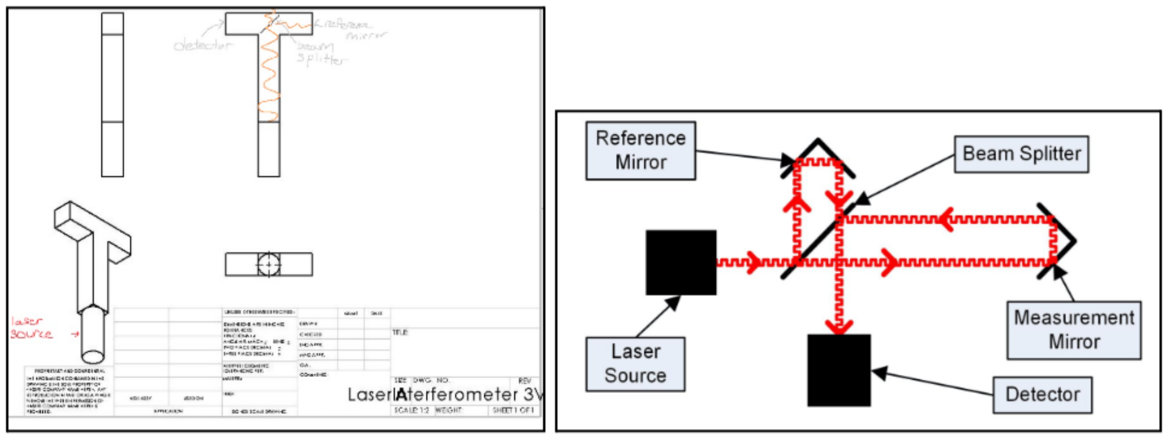
Material Choice & Rankings for Oxidation Resistance					
Ideas	**Is a Metal?**	**Carrier Gas?**	**Density**	**Energy required to vaporize**	Points (higher is better)
Chromium	TRUE	TRUE	1	0.5738333333	0.1065416667
Silicon Dioxide	FALSE	FALSE	0.3682892907	1	-0.2684144645

Material Choice & Rankings for IR Reflection (For maintaining temperature)					
Ideas	**Reflectance**	**Carrier Gas?**	**Density**	**Energy required to vaporize**	Points (higher is better)
Aluminum	0.992970476	FALSE	0.1398963731	0.9549829246	0.2507446882
Gold	1	FALSE	1	0.96522819	0.2086929525
Copper	0.9996987347	FALSE	0.4642487047	1	0.2266369321

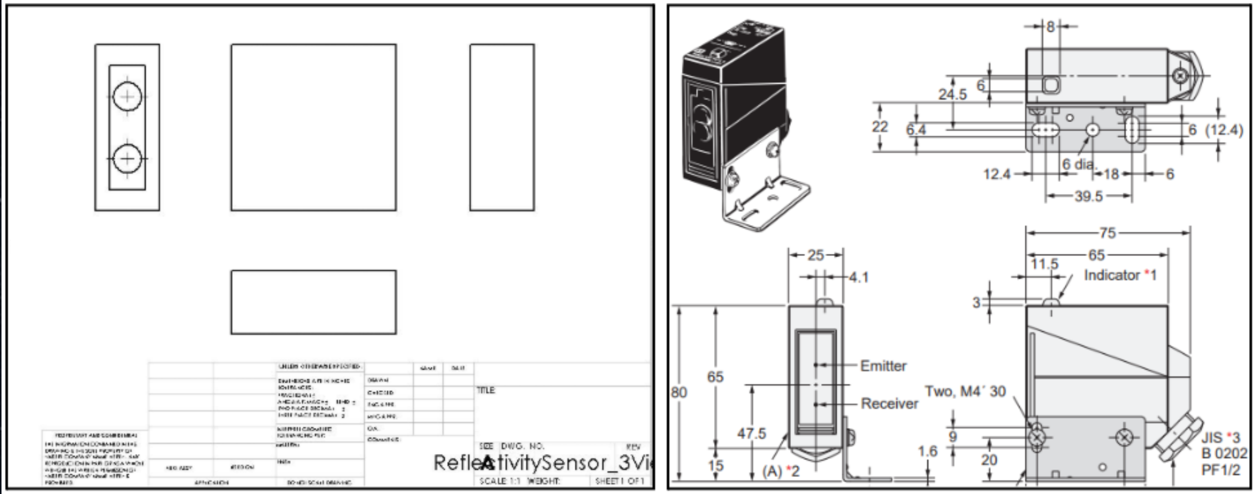
Category	**Criteria**	**Weight**
Reflectance	**Thermal Reflectivity constant**	**50%**
Sustainability	**Does it recquire a carrier gas for deposition**	**20%**
Density	**Density in g/cm^3 (weight needed to coat a certain amount of surface area)**	**5%**
Energy Required	**Latent heat of evaporation in kJ / mol**	**25%**
Total		**100%**

Surface Characterization Subsystem (Continued)

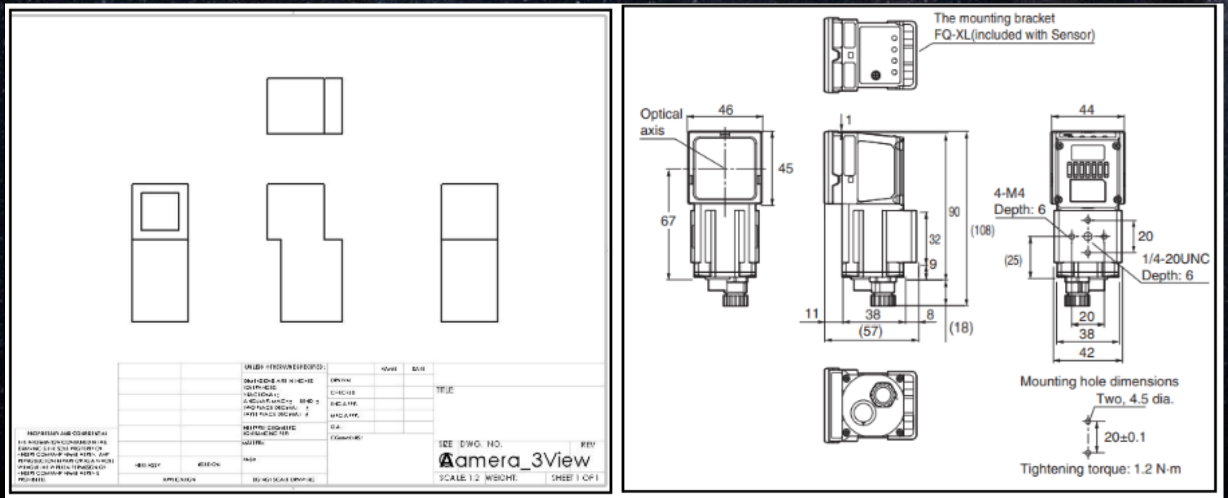
Sensors CAD Designs



CAD design of the laser interferometer (left), modeled after a conceptual diagram (right) made by Dr Jody Muelaner on Engineering.com



CAD design of the photo-electric sensor (left), modeled after the E3JK sensor made by the OMRON Corporation (right)



CAD design of the camera sensor (left), modeled after the FQ2 camera made by the OMRON Corporation (right)

- The sensors that are used for the surface characterization are modeled after commercially-available ones
- The reflectivity sensor and the digital camera are modeled after from Omron Industrial Automation's E3JK and FQ2 sensors, respectively
- The laser interferometer was designed from scratch using a conceptual diagram of the laser path

Link Budget

Downlink

Item	Symbol	Units	Source	Cmd to orbiter
Freq.	f	Ghz	input	**8.00**
Xmtr Pwr	P	W.	input	**4.0000**
Xmtr Pwr	P	dbW	10 log(P)	6.02
Xmtr line loss	L_l	dB	input	**-1.00**
Xmtr Ant. Beamwidth	θ_t	deg	Eq. (13-19)	62.950
Peak Xmt. Ant. Gain	G_{pt}	dB	Eq. (13-20)	8.32
Xmt. Ant. Diam.	D_t	m	input	**0.04**
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	$G_{pt}+L_{pt}$	8.32
EIRP	EIRP	dB	$P+L_l+G_t$	13.34
Prop. Path Length	S	km	input	**1.878E+03**
Space Loss	L_s	dB	Eq. (13-23a)	-175.98
Prop. & Polariz. Loss	L_a	dB	Fig. 13-10	**-0.05**
Rcv. Ant. Diam.	D_r	m	input	**5.40**
Peak Rcv. Ant. Gain	G_{rp}	dB	Eq. (13-18a)	50.52
Rcv. Ant. Beamwidth	θ_r	deg	Eq. (13-19)	0.49
Rcv. Ant. Pointing Error	e_r	deg	input	**0.05**
Rcv. Ant. Pointing Loss	L_{pr}	dB	Eq. (13-21)	-0.13
Rcv. Ant. Gain	G_r	dB	$G_{rp}+L_{pr}$	50.40
System Noise Temp.	T_s	K	input (using Tabl	**135.00**
Data Rate	R	bps	input	**3500000.00**
Est. E_b/N_o (1)	E_b/N_o	dB	Eq. (13-13)	29.57
Bit Error Rate	BER	--	input	**1.0E-05**
Rqd. E_b/N_o (2)		dB	Fig. 13-9 (BPSK,	**4.50**
Implementation Loss (3)		dB	input (standard	**0.00**
Margin		***dB***	***(1)-(2)+(3)***	***25.07***

Space Coatings

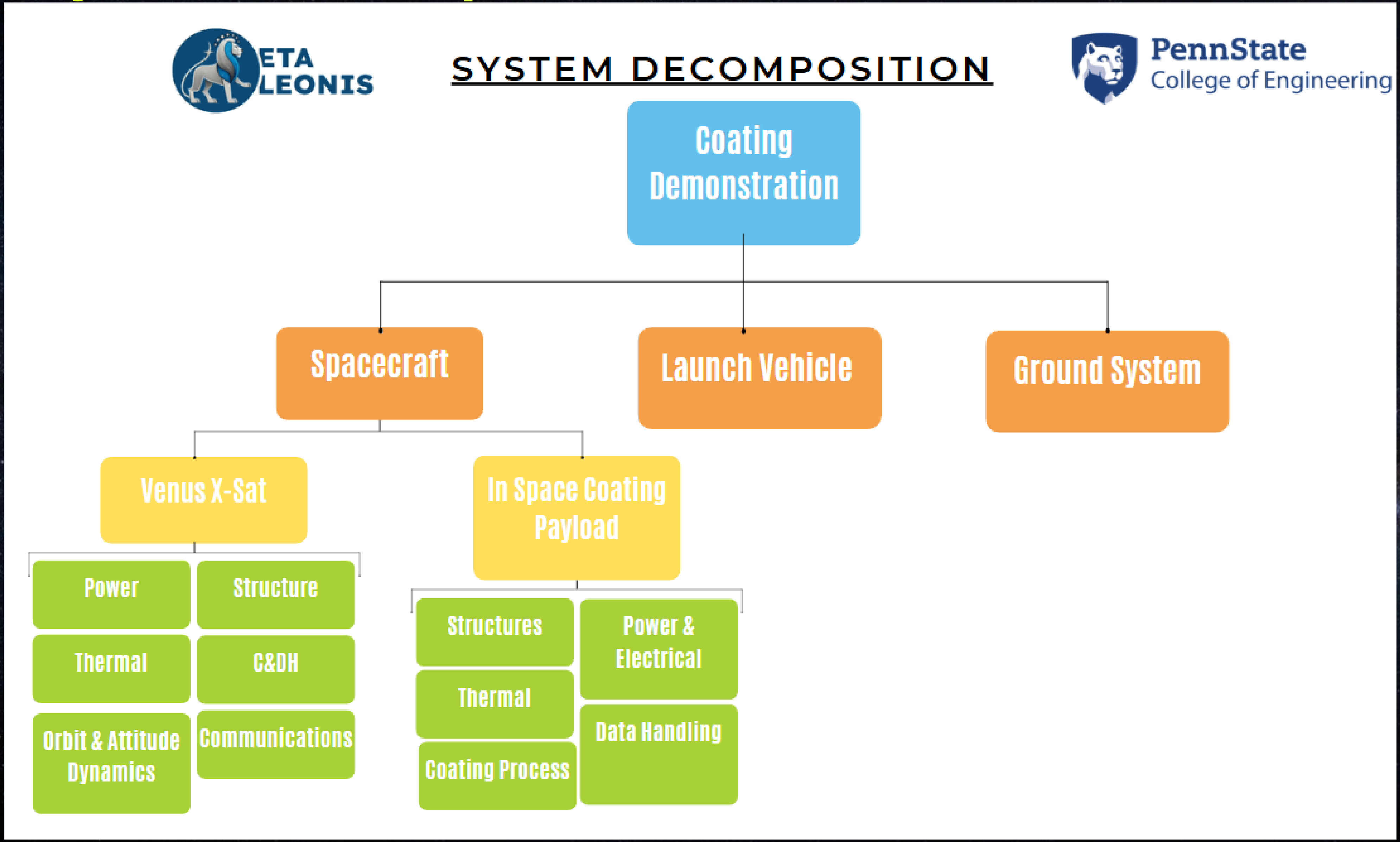
Link Budget

Uplink

Item	Symbol	Units	Source	Cmd to orbiter
Freq.	f	Ghz	input	**4.00**
Xmtr Pwr	P	W.	input	**4.0000**
Xmtr Pwr	P	dbW	10 log(P)	6.02
Xmtr line loss	L_l	dB	input	**-1.00**
Xmtr Ant. Beamwidth	θ_t	deg	Eq. (13-19)	0.972
Peak Xmt. Ant. Gain	G_{pt}	dB	Eq. (13-20)	44.54
Xmt. Ant. Diam.	D_t	m	input	**5.40**
Xmt. Ant. Pointing Error	e_t	deg	input	**0.05**
Xmt. Ant. Pointing Loss	L_{pt}	dB	Eq. (13-21)	-0.03
Xmt Ant. Gain	G_t	dB	$G_{pt}+L_{pt}$	44.51
EIRP	EIRP	dB	$P+L_l+G_t$	49.53
Prop. Path Length	S	km	input	**1.878E+03**
Space Loss	L_s	dB	Eq. (13-23a)	-169.96
Prop. & Polariz. Loss	L_a	dB	Fig. 13-10	**-0.05**
Rcv. Ant. Diam.	D_r	m	input	**0.04**
Peak Rcv. Ant. Gain	G_{rp}	dB	Eq. (13-18a)	1.90
Rcv. Ant. Beamwidth	θ_r	deg	Eq. (13-19)	131.25
Rcv. Ant. Pointing Error	e_r	deg	input	**0.05**
Rcv. Ant. Pointing Loss	L_{pr}	dB	Eq. (13-21)	0.00
Rcv. Ant. Gain	G_r	dB	$G_{rp}+L_{pr}$	1.90
System Noise Temp.	T_s	K	input (using Table 13-10)	**135.00**
Data Rate	R	bps	input	**1500000.00**
Est. E_b/N_o (1)	E_b/N_o	dB	Eq. (13-13)	26.96
Bit Error Rate	BER	--	input	**1.0E-05**
Rqd. E_b/N_o (2)		dB	Fig. 13-9 (BPSK, R-1/2 Viterbi)	**4.50**
Implementation Loss (3)		dB	input (standard estimate)	**0.00**
Margin		***dB***	***(1)-(2)+(3)***	***22.46***

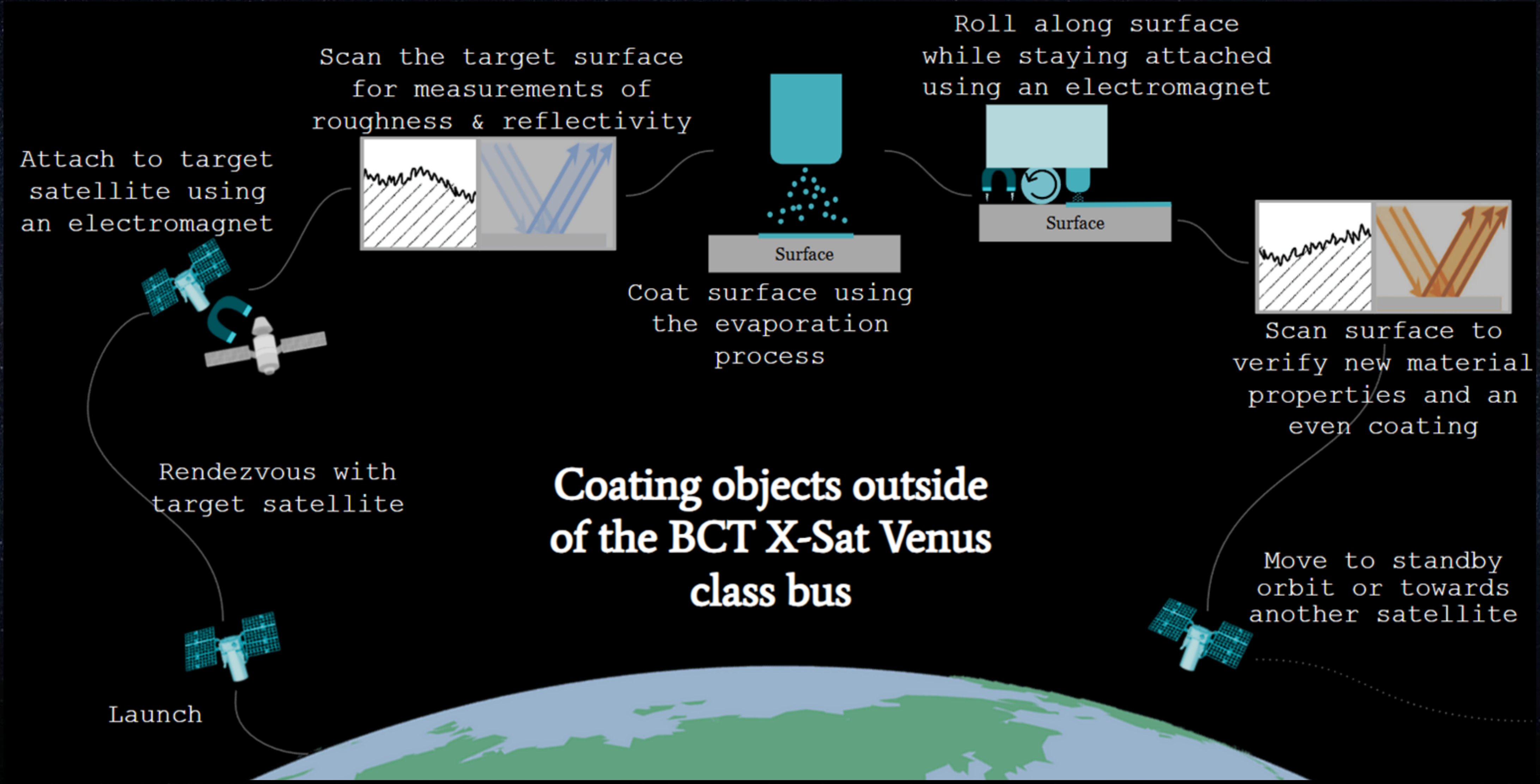
Space Coatings

Subsystem Decomposition



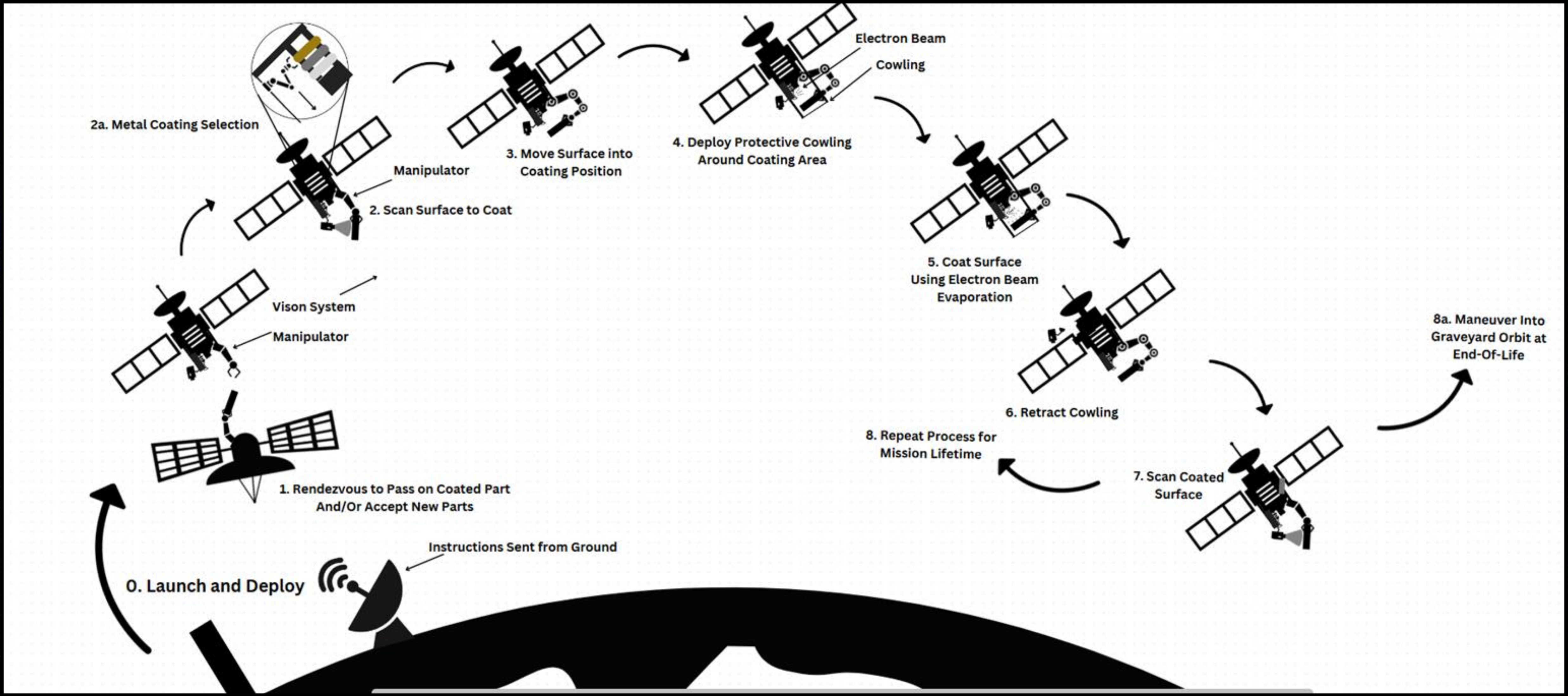
Other CONOPS Ideas

The External Method



Other CONOPS Ideas (continued)

The Hybrid Method



Functional Analysis