PERCI

Penetrator for Environmental, Regolith, and Crater Investigation

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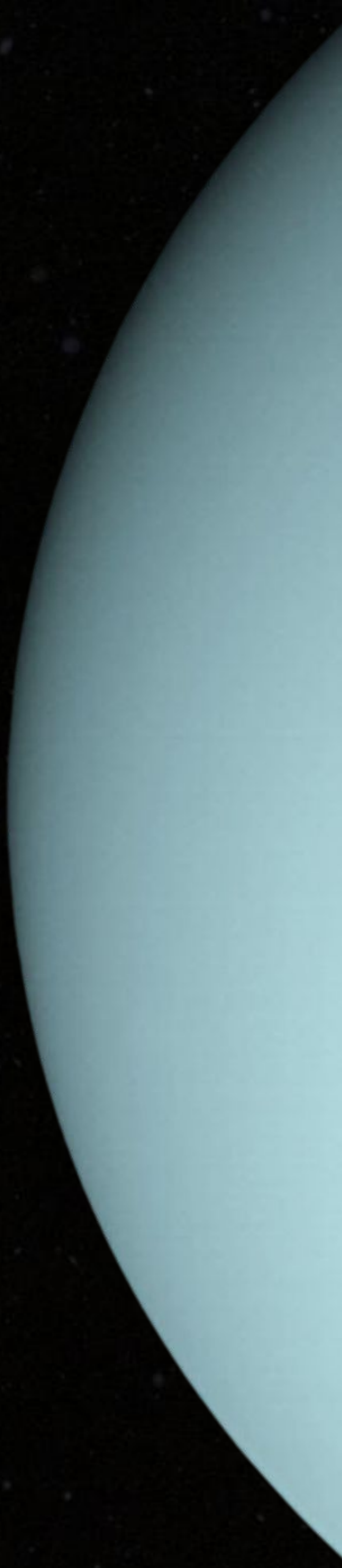
Agenda

- Team
- Challenge & Approach
- Scope
- Mission Concept
- Task Organization
- Execution Path
- Science
- System Requirements
- Subsystems
- Conops
- Risk
- Budgets
- Schedule
- Future Work
- Conclusion



Team


Ted


Tao


Jay


Rawan


Will


Miguel


Kim


Sanjana


Aryanna


Stevie


Saima


Samantha


Sean


Rahul

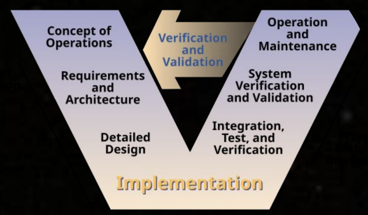
Mentors


Buzz
Emotional Support
Mentor


Dillan McDonald
Mentor


Ananyo Bhattacharya
Mentor

Honorable Mention



Team Structure

Team Lead
Ted Saenger

- **Systems Lead** – Rawan Aljaber
  - Tao
  - Will
  - Samantha
  - Ted
- **Science & PYLD Lead** – Ted Saenger
  - Rahul
  - Kimberly
  - Aryanna
  - Will
  - Miguel
  - Saima
- **Propulsion Lead** – Jayveer Phull
  - Stephen
  - Sanjana
  - Samantha
- **ADCS Lead** – Sanjana Kerkar
  - Jayveer
  - Samantha
  - Saima
- **Power/Comms Lead** – Sean McClary
  - Samantha
  - Ted
  - Jayveer
- **Structures Lead** – Jayveer Phull
  - Ted
  - Kimberly
  - Stephen
  - Will
  - Miguel
  - Saima
- **Thermal Lead** – Tao Sevigny
  - Rawan
  - Jayveer
  - Ted

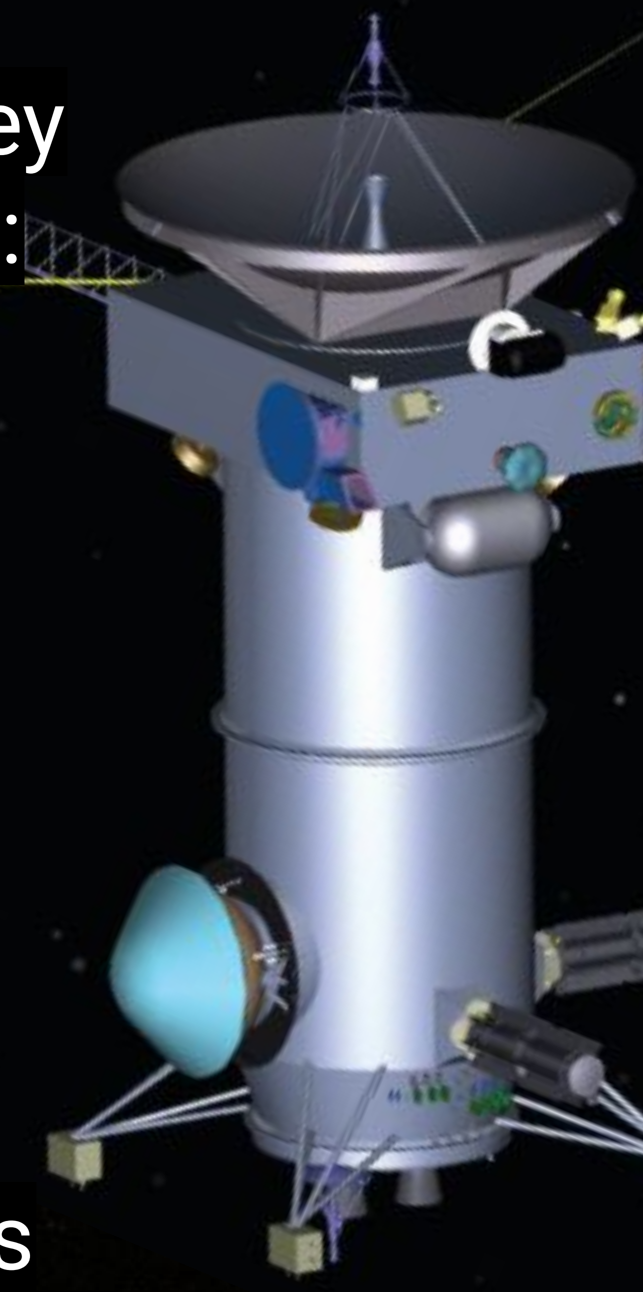
Challenge & Approach

Challenge:

- Enhance the science return of NASA's Uranus Orbiter & Probe (UOP) mission, the top priority of the 2023-2032 Planetary Science Decadal Survey
- UOP to conduct multi-year observations of the Uranian system focused on:
  - Planet's origin, interior and atmosphere
  - Magnetic field and magnetosphere
  - Uranian satellites and ring system

Our Approach:

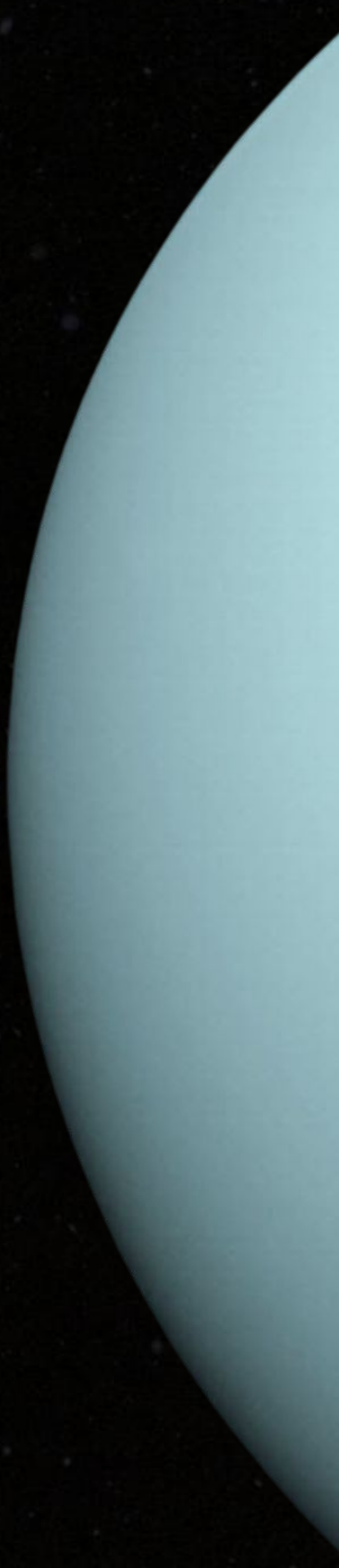
- Work closely with mentors to refine mission constraints and feasibility
- Use NASA SIMPLEx as a guideline, allowing flexibility for mission needs
- Develop a small, secondary spacecraft to accompany the main mission
- Focus on major Uranian satellites: Miranda, Ariel, Titania, Oberon, Umbriel
- Align design with Decadal Survey priorities and scientific community needs
- Draw inspiration from mission concepts like Europa Clipper & Huygens Probe



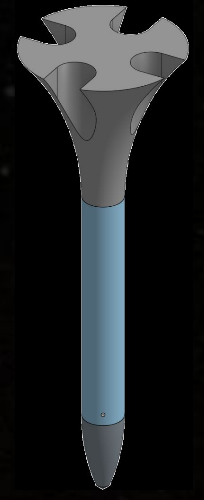
Project Scope & Deliverables

By the end of project the following deliverables will be produced:

- [x] Science Traceability Matrix
- [x] Science instruments recommendations and trades studies
- [x] Top-level, system-level, and subsystem-level requirements
- [x] Concept of Operations architecture
- [x] Spacecraft design decisions with relevant trade studies
- [x] Risk and budget analysis
- [x] Final report on work accomplished
- [ ] Academic paper for conference



Mission Concept - PERCI

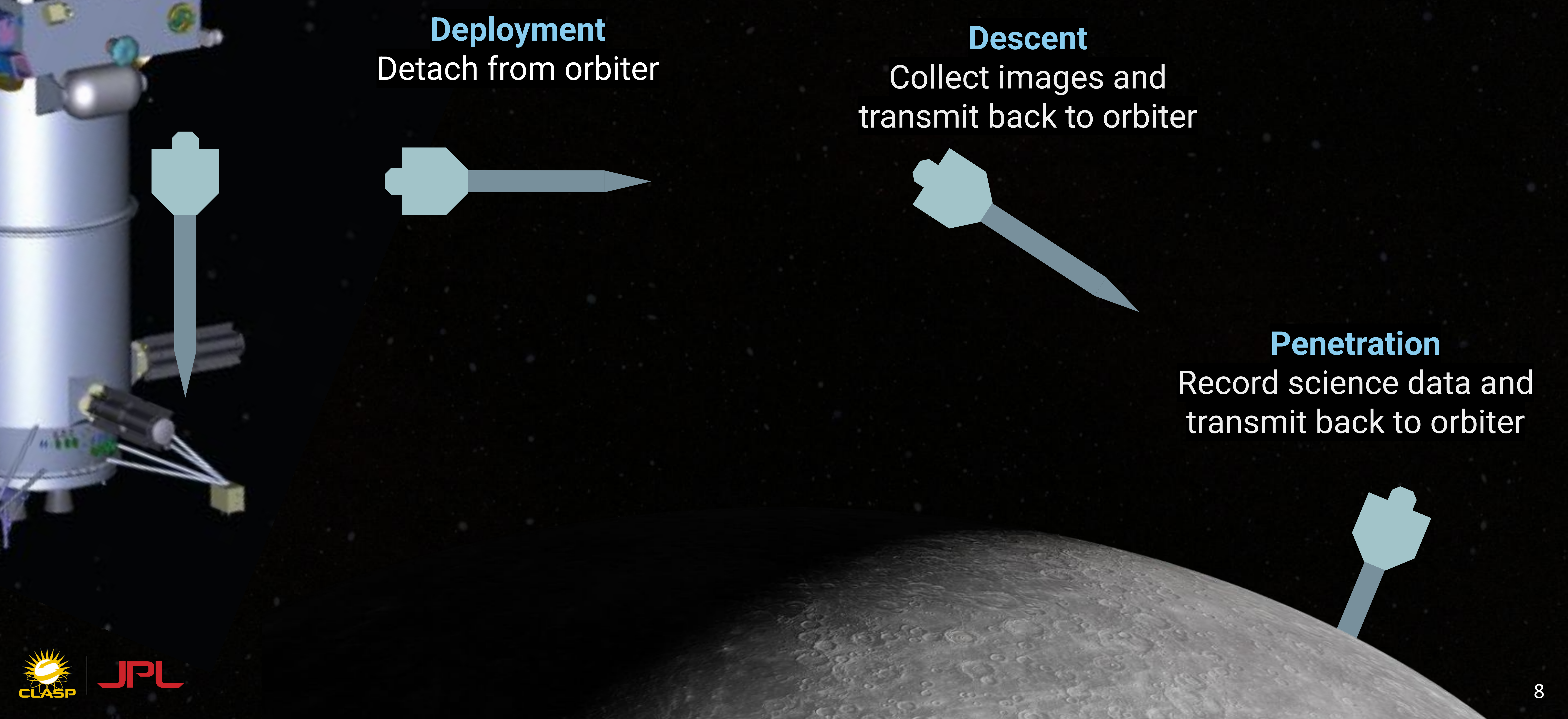


- Penetrator spacecraft
- Separates from UOP and enter an impact trajectory into a selected target moon
- Impact creates a debris cloud for UOP observance
- On impact survival, can measure surface science data
- Data is compressed and transmitted to UOP using the same comms architecture as the UOP probe

Pentrator CAD,
w/ SRBs

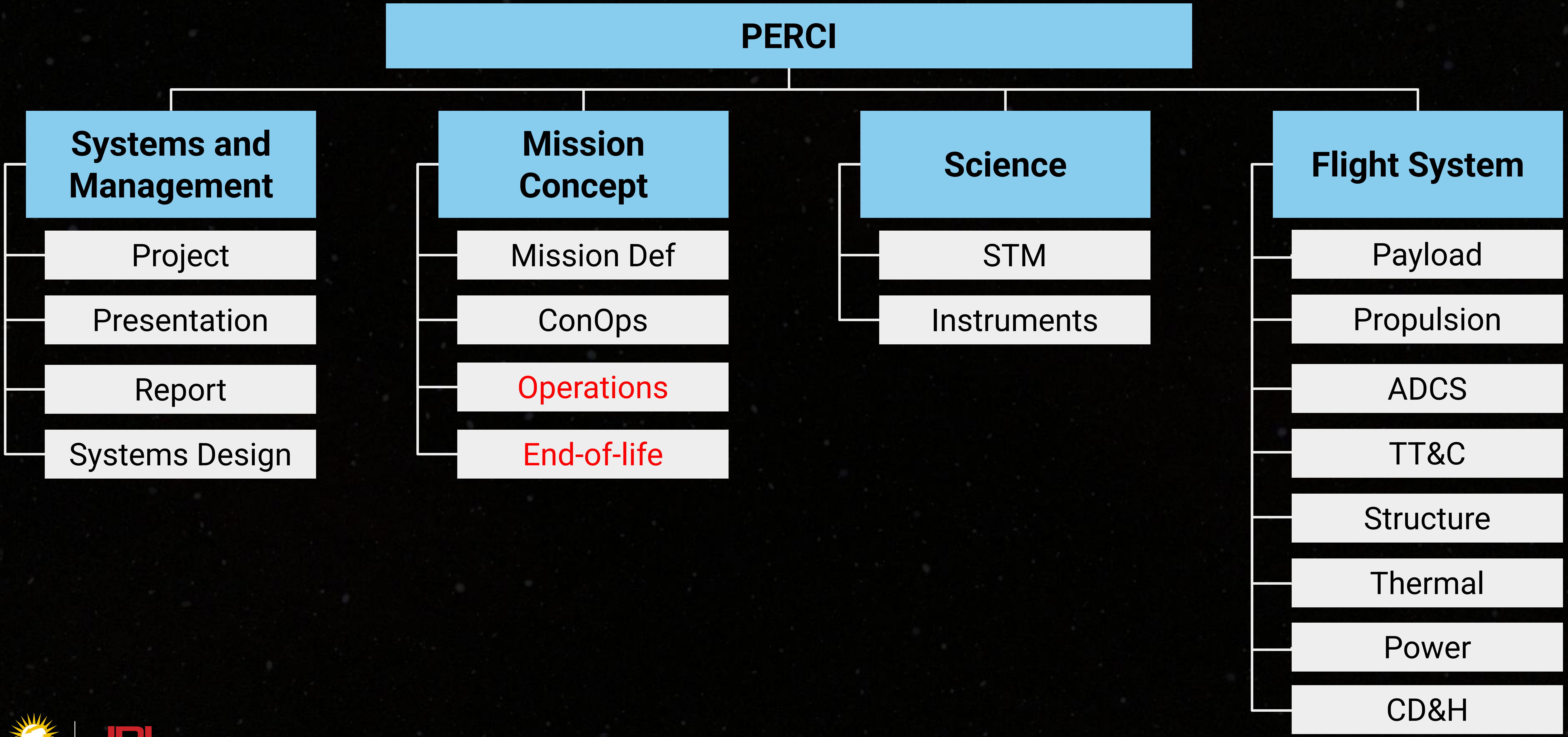
Pentrator CAD,
w/o SRBs

Mission Concept (Cont.)

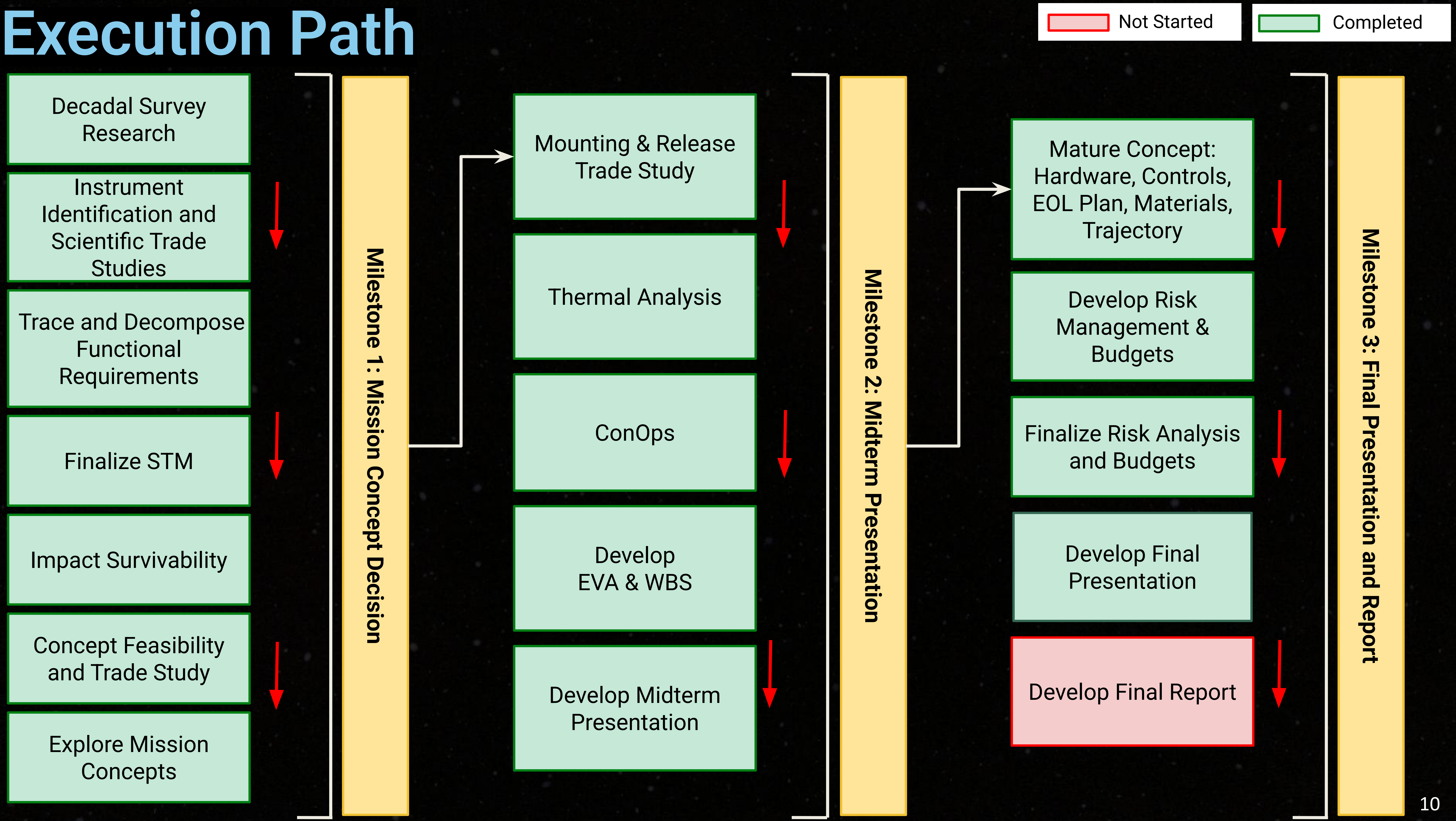


Task Organization

*out of scope



Execution Path



Approach to Science Enhancement

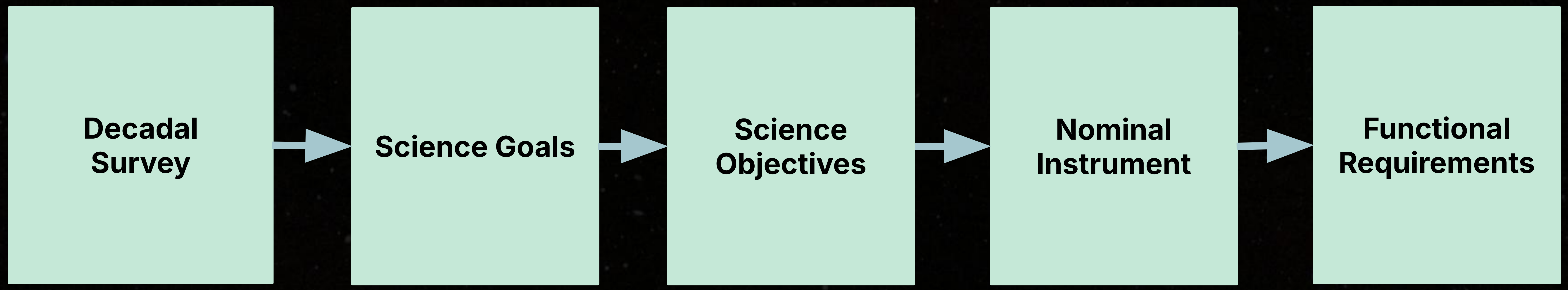
What can PERCI accomplish that the UOP mission cannot by itself ?

- In-situ surface measurements represent a weakness in the UOP's science return that this secondary payload can strengthen
- PERCI can support the UOP's analysis of Uranian satellites to provide more science return

Objectives:

- Quantify chemical abundances from impact plumes
- Measure surface composition, topography, and mineralogy
- Measure surface hardness and conduct ice failure tests
- Observe impact events and ejecta distribution (surface, escape, orbit)
- Determine interior structure and ice sheet thickness
- Measure thermal conductivity and surface heat dissipation patterns

Science Traceability



Science Traceability Chart (1/4)

Decadal Survey	Q12.8a What Can Observations of Material Reveal About Formation of Circumplanetary Systems?	Q4.4b What Materials Ejected from Impact Craters Are Deposited on Planetary Surfaces?	Q5.1c How Does Porosity, Ices, Liquids, or Gases Affect the Physical Properties of the Crust?	Q5.1a How Much Variability in Composition and Internal Structure Is There Within and Between Solid Bodies, and How Did Such Variability Arise and Evolve?	Q8.2f How Are Heat and Material Transported Through—and Ultimately Out of—Satellite Interiors?
Science Goals	Collect images of the surface	Determine the chemical composition of the moon's surface	Determine the physical properties of the large moon's surface at the point of impact	Probe the interior of the Uranian satellites	Determine the thermal properties of the moon's surface
Science Objectives / Measurements					
Nominal Instrument					
Functional Requirements					

Science Traceability Chart (2/4)

Decadal Survey

Science Goals

Science Objectives / Measurements

Nominal Instrument

Functional Requirements

Science Goals	Collect images of the surface	Determine the chemical composition of the moon's surface	Determine the physical properties of the large moon's surface at impact	Probe the interior of the Uranian satellites	Determine the thermal properties of the moon's surface
Science Objectives / Measurements	Determine the surface topography Images of surface in nadir and azimuth	Identify and quantify the relative abundances of key chemical elements and minerals present on the moon's surface from the impact plume Vis/NIR Spectroscopy Species: 1.5-2.5 um (H_2O, C, silicates)	Determine the surface hardness of the Uranian moons Deceleration profile	Determine the interior composition and structure of the Uranian moons Determine the thickness of the ice sheet Seismic noise: Coda of body waves, harmonic frequency of Crary Waves	Determine the thermal conductivity and heat dissipation rates as well as their variation at different (2) depths Post-impact temperature decay

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Science Traceability Chart (3/4)

Decadal Survey					
Science Goals					
Science Objectives / Measurements	Determine the spectral composition and topography of the surface Images of surface in nadir and azimuth	Identify and quantify the relative abundances of key chemical elements and minerals present on the moon's surface from the impact plume Vis/NIR Spectroscopy Species: H_2O, CO_2, CH_4, N_2	Determine the surface hardness of the Uranian moons Conduct in-situ ice failure studies on the surface Deceleration profile	Determine the interior composition and structure of the Uranian moons Determine the thickness of the ice sheet Seismic noise: Coda of body waves, harmonic frequency of Crary Waves	Determine the thermal conductivity and heat dissipation rates as well as their variation across the surface Post-impact temperature decay
Nominal Instrument	Downward-facing multi-spectral imager (R, G, B, NIR-1, NIR-2; 10 meter resolution) Side-view imager (Visible; 10 meter resolution)	Vis/NIR Imaging Spectrometer	Accelerometer	Seismometer	Resistive Temperature Detector
Functional Requirements					

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Science Traceability Chart (4/4)

- Decadal Survey
- Science Goals
- Science Objectives / Measurements
- **Nominal Instrument**
- **Functional Requirements**

Nominal Instrument	Downward facing imager (R, G, B, NIR-1, NIR-2; 10 meter resolution) Side-view imager (Visible; 10 meter resolution)	Vis/NIR Imaging Spectrometer & WAC (Lucy L'Ralph on flagship)	Accelerometer	Seismometer	Resistive Temperature Detector
Functional Requirements	Image capture, processing, transmission during descent Stable descent trajectory.	Maintain line of sight with the orbiter	Record data at [TBR] readings/sec	High shock tolerance High signal to noise ratio	Low temperature operation High-frequency temperature readings post-impact Probe at least [TBR] meters into the surface

Instrument Suite Summary

<u>Trade studies</u> were conducted to select the following payload instruments

Instrument	Instrument Selection	Important Criteria
Camera	OSIRIS REX SamCam/TAGCAMS (ECAM M50)	• High survivability (radiation/thermal) • Excellent operation in low light conditions
Imaging Spectrometer	Vis/NIR Imaging Spectrometer & WAC (Lucy L'Ralph on flagship)	• Spectral Imaging allows for surface composition data • Offset to orbiter, more simplicity
Accelerometer	PCB Piezotronics Accelerometer	• Sufficiently large temp. operating range • High amplitude range / shock tolerance
Seismometer	Artius Seismometer	• Broad spectrum for high and low freq. vibration • High tilt tolerance
Thermal Probe	Cernox RTD	• Quick Thermal Response Time • High Measurement Reproducibility

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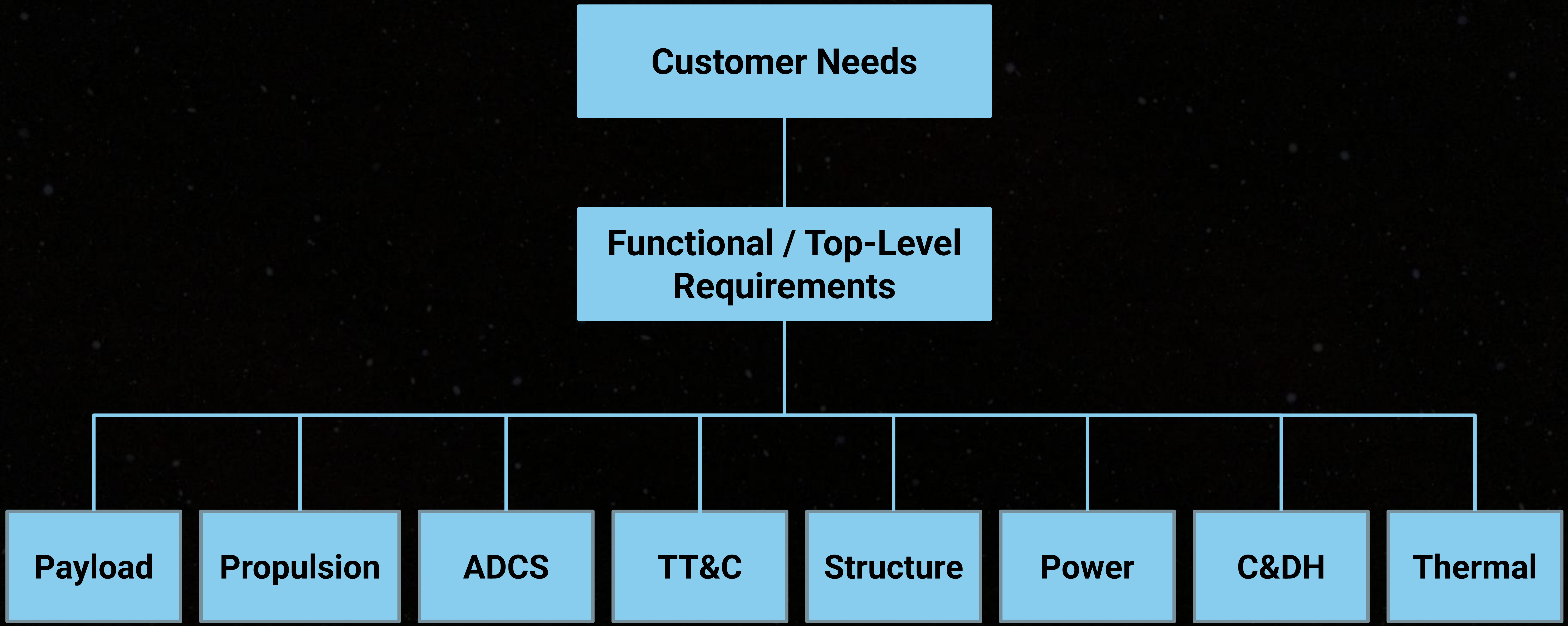
Requirements Flowdown



Customer Needs

ID	Requirement Name	Justification	Verification Method
SYS_CN_1	Sizing Needs	The system assembly shall fit within the payload fairing of the launch vehicle	Inspection
SYS_CN_2	Enhance Science	The system shall enhance the scientific objectives of the UOP mission	Analysis / Test
SYS_CN_3	TRL	The system shall use COTS and TRL 6+ technology	Inspection / Analysis
SYS_CN_4	SIMPLEX Need	The system shall adhere to NASA's SIMPLEx program	Inspection
SYS_CN_5	Power	The system shall not exceed a power draw of [2W] from the flagship	Analysis / Test
SYS_CN_6	Impedance	The system shall not impede performance of the flagship mission	Analysis / Test
SYS_CN_7	Do No Harm	The system shall do no harm to the flagship	Analysis / Test
SYS_CN_8	Data Transmission	The system shall transmit all data to the orbiter at a maximum data rate of 20.1 kbps	Analysis / Test

Top Level Requirements

ID	Requirement Name	Justification	Verification Method
SYS_TL_1	Science Goals	The system shall support the current NASA planetary science goals	Analysis
SYS_TL_2	Planetary Protection	The system shall adhere to the NASA planetary protection guidelines for forward contamination	Inspection / Test
SYS_TL_3	Orbiter ΔV	The system separation from the orbiter shall not impede the Orbiter's trajectory	Analysis / Test
SYS_TL_4	Heat Flow	The system shall not have greater than [TBR] W of heat flow to/from the flagship	Analysis / Test
SYS_TL_5	Temperature	The system shall maintain all components within their temperature limits with ±5°C margin	Analysis / Test

Constraints

ID	Requirement Name	Justification	Verification Method
SYS_C_1	SIMPLEX Constraint	The system shall meet the critical development milestones per the NASA SIMPLEx guidelines	Inspection
SYS_C_2	Mass Constraint	The system shall not exceed a wet mass of 180 kg	Inspection
SYS_C_3	Volume Constraint	The system should not exceed a total volume of 0.42 m^3/(1.19 m^3 w/ESPA ring)	Inspection
SYS_C_4	Cost Constraint	The system should not exceed a cost of $55 million for all mission phases	Analysis
SYS_C_5	Comms Constraints	The system shall be able to communicate with the main orbiter	Analysis / Test
SYS_C_6	Fairing Constraint	The system, when integrated with the UOP system, shall fit within the Falcon heavy fairing volume	Inspection

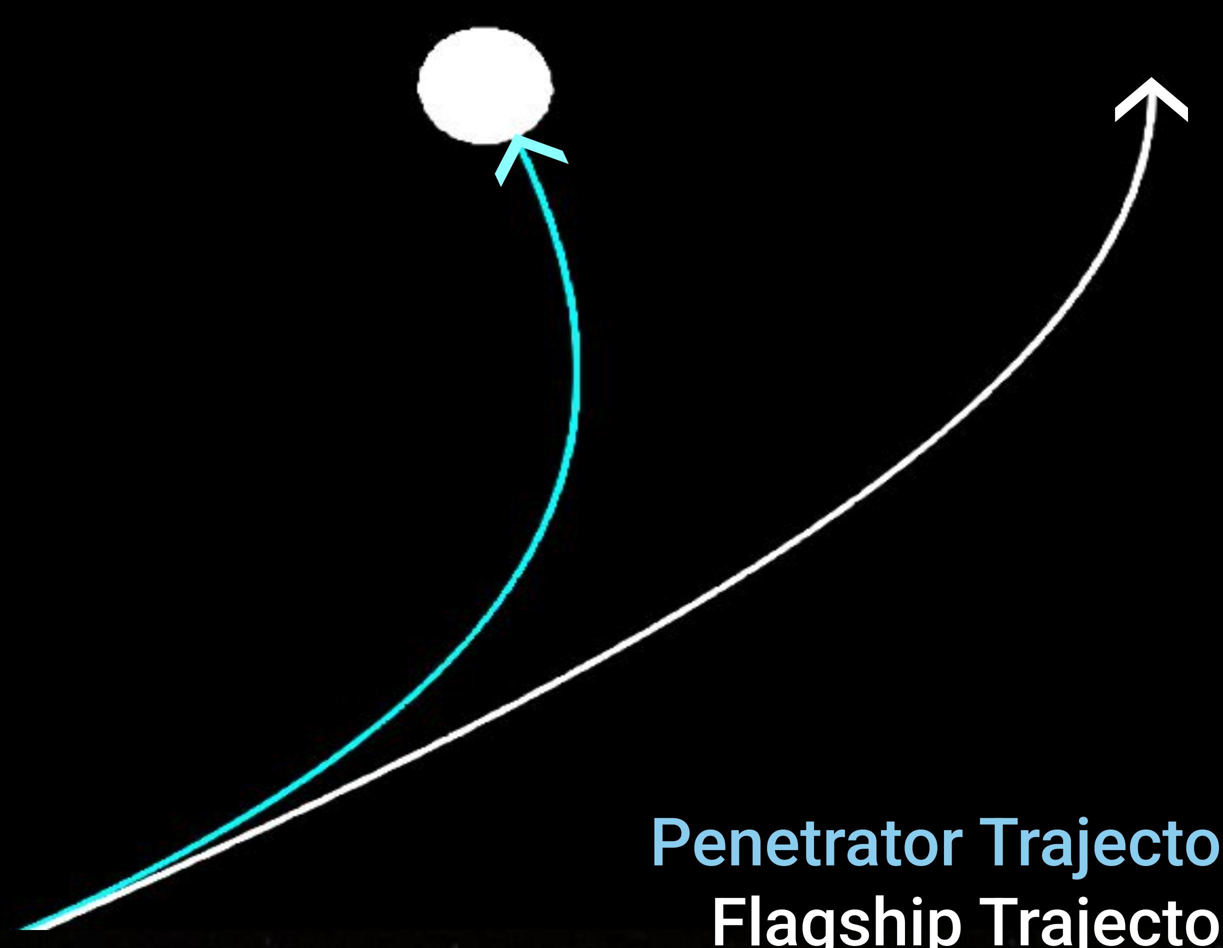
PERCI Mission Functional Requirements

ID	Requirement Name	Justification	Verification Method
SYS_MFR_1	Mission Support	The system shall support continuous operation to payload, CDH, TT&C, power, and thermal subsystems	Analysis
SYS_MFR_2	Pointing Stability	The system shall have appointing stability of [TBR] (such to reduce image blur) during descent trajectory	Analysis / Test
SYS_MFR_3	Shielding	The system shall shield the imagers from dust and other hazards during approach and descent	Analysis / Test
SYS_MFR_4	Survival	The system should survive the impact, with all necessary components still operational	Analysis
SYS_MFR_5	Deceleration Profile	The system should record the deceleration profile at the time of impact.	Analysis

Subsystems

Trajectory Analysis Overview

- Approximate flagship trajectory around target moons
  - Based on deployment location and ΔV
- Optimize trajectories
  - Feasible ΔV
  - Minimize impact velocity
  - Impact angle close to 90°
  - Line of sight of flagship



Moon	Flyby	Time Before Closest Approach [hrs]	ΔV [m/s]	Impact Velocity [m/s]	Impact Angle [deg]	Flight Duration [hrs]
Ariel	7/29/47	3.0	479	1170	89	2.8
Oberon	7/28/47	4.7	414	1397	84	6.1
Titania	8/11/45	2.5	820	2258	85	3.3
Umbriel	6/22/47	4.4	415	901	86	4.2

Trajectory Analysis Overview

- Approximate flagship trajectory around target moons
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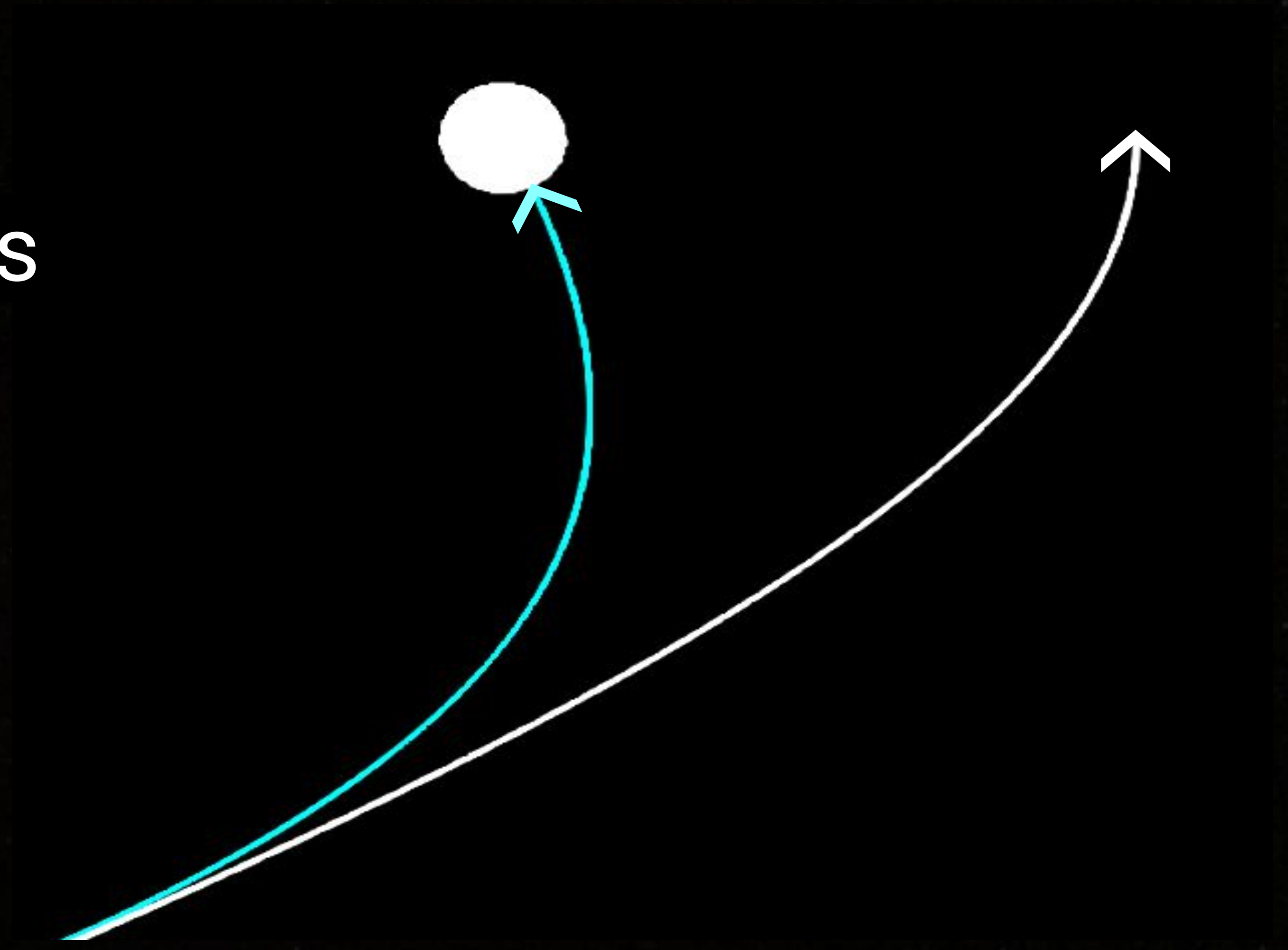

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Propulsion Requirements

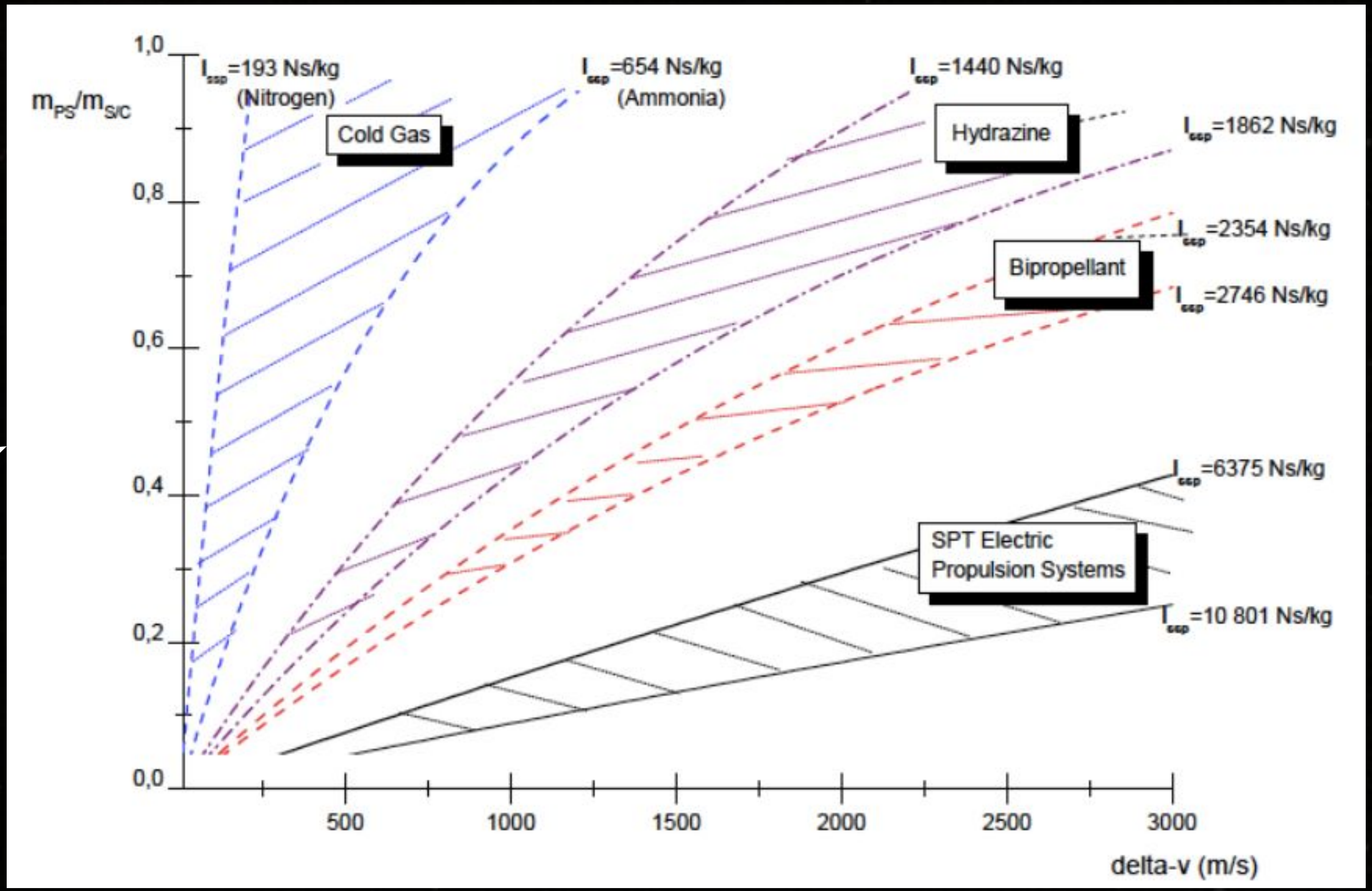
Propulsion subsystem shall:

- Provide a minimum of 450 m/s of delta-V during all relevant mission phases
- Decouple from the penetrator prior to impact
- Be kept within survival temperatures during all mission phases
- Be kept within operating temperatures during the required mission phases
- Have COTS components with TRL 6+

Propulsion Overview (1/2)

Solid Rocket Booster (SRBs) would be the best for this mission as they are:

- Inert
- Easy to start
- Will not leak propellant
- Low cost
- Weight can be shed for lower impact energy
- Low battery power requirement
- Meets Do No Harm Requirements
- High Delta V @ low prop mass/volume



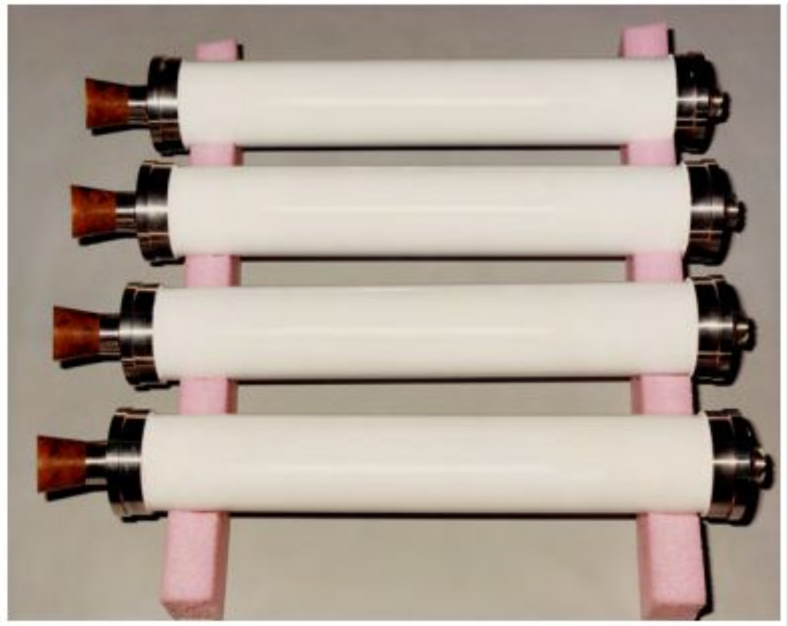
Delta V Limits Based on Propellant-Spacecraft Mass Ratio and Propellant

Propulsion Overview (2/2)

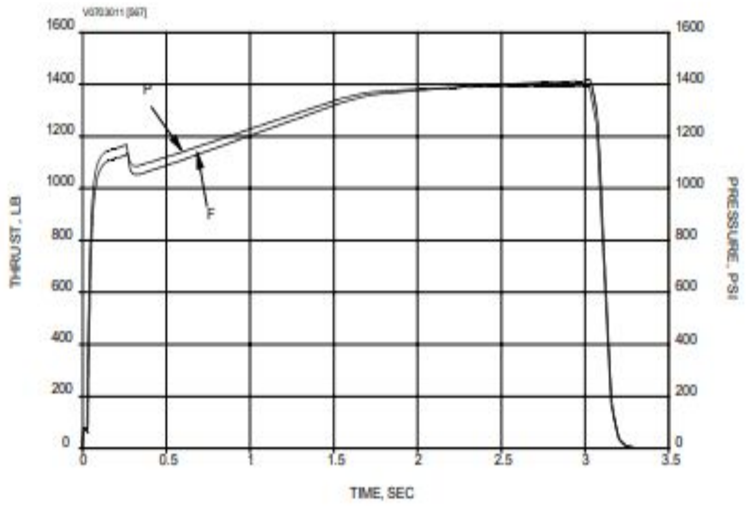
Initial Constraints					
SRB	**Total Impactor Mass**	**SRB Loaded Mass**	**SRB Empty Mass**	**ISP**	**g**
Star 5D:	160Kg	10.23Kg	3.32Kg	256 Seconds	9.81 m/s²

# Of Motors	ΔV
1 Motor	139 m/s
2 Motors	265 m/s
3 Motors	379 m/s
4 Motors	476 m/s

Note: ADCS thrust vectoring can be used to meet ΔV requirements for the intended trajectory.



The STAR 5D rocket motor was designed and qualified (1996) to serve as the rocket-assisted deceleration motor on the Mars Pathfinder mission for the Jet Propulsion Laboratory (JPL) in Pasadena, CA. The STAR 5D features a titanium case, head-end ignition system, and canted nozzle design and is based on earlier STAR 5 designs. Three of these motors were fired on July 4, 1997, to slow the Pathfinder spacecraft to near-zero velocity before bouncing on the surface of Mars.



MOTOR DIMENSIONS
Motor diameter, in. 4.88
Motor length, in. 32.7

MOTOR PERFORMANCE (-22°F VACUUM)
Burn time/action time, sec 3.03/3.28
Ignition delay time, sec 0.029
Burn time average chamber pressure, psia 1,299
Maximum chamber pressure, psia 1,406
Total impulse, lbf-sec 3,950
Propellant specific impulse, lbf-sec/lbm 259.5
Effective specific impulse, lbf-sec/lbm 256.0
Burn time average thrust, lbf 1251
Maximum thrust, lbf 1,410

NOZZLE
Initial throat diameter, in. 0.869
Exit diameter, in. 2.345
Expansion ratio, initial 7.3:1
Cant angle, deg 17

WEIGHTS, LBM
Total loaded 22.55
Propellant (including igniter propellant) 15.22
Case assembly 5.93
Nozzle assembly 1.40
Total inert 7.33
Burnout 7.12
Propellant mass fraction 0.68

TEMPERATURE LIMITS
Operation .... -67°-158°F
Storage .... -80°-172°F

PROPELLANT DESIGNATION TP-H-3062

CASE MATERIAL .... TITANIUM

PRODUCTION STATUS
.... FLIGHT-PROVEN

$$\Delta v = \left(v_e := I_{sp} * g_0\right) * \ln\left(\frac{m_0}{m_f}\right)$$

Delta V equation and SRB Data Sheet

SRB Mounting/Ejection

To minimize risk/potential damage to the spacecraft

- SRBs will be mounted with the nozzles facing aft via spring lock mechanism
  - Avoids the hot gasses from interfering with the main body/tip
- Staggered SRB ejection to induce a 180° rotation without ADCS to prevent saturation
  - Allows for the tip to point in the direction of travel
  - Spring loaded ejection with burn wire trip
  - Spacecraft flip slew rate to not exceed 10°/sec

Penetrator CAD

ADCS Requirements

ADCS subsystem shall:

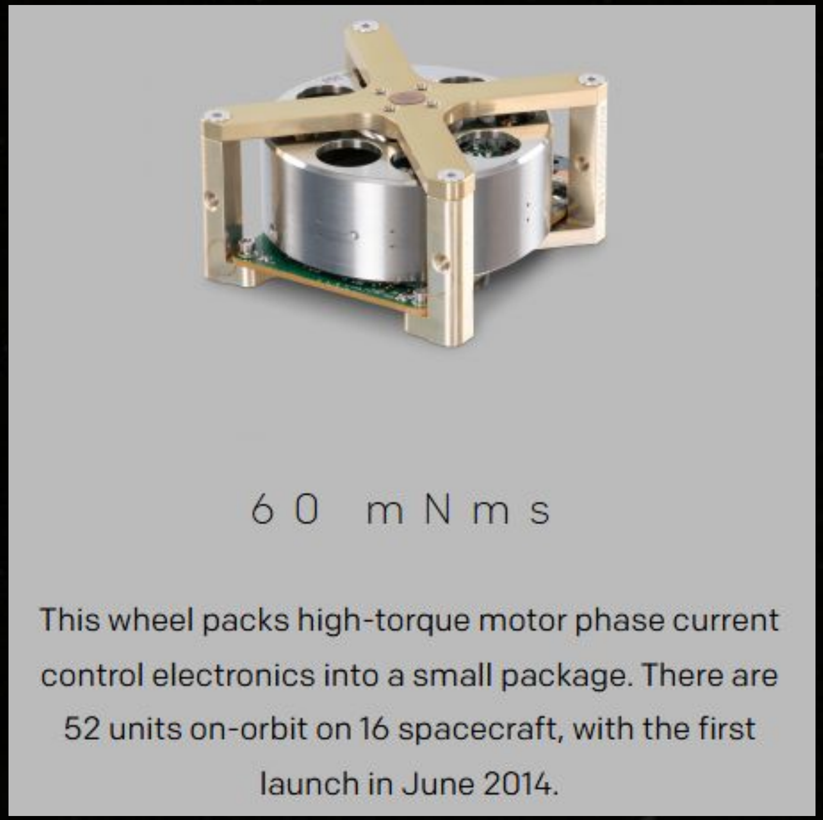
- Provide accurate pointing within 1° post SRB burn to support communications with Flagship Orbiter
- Provide accurate pointing within 1° during the descent/pre-impact phase
- Provide pointing stability of [TBR] during descent phase
- Have all components be COTS with a TRL of 6+

ADCS Design

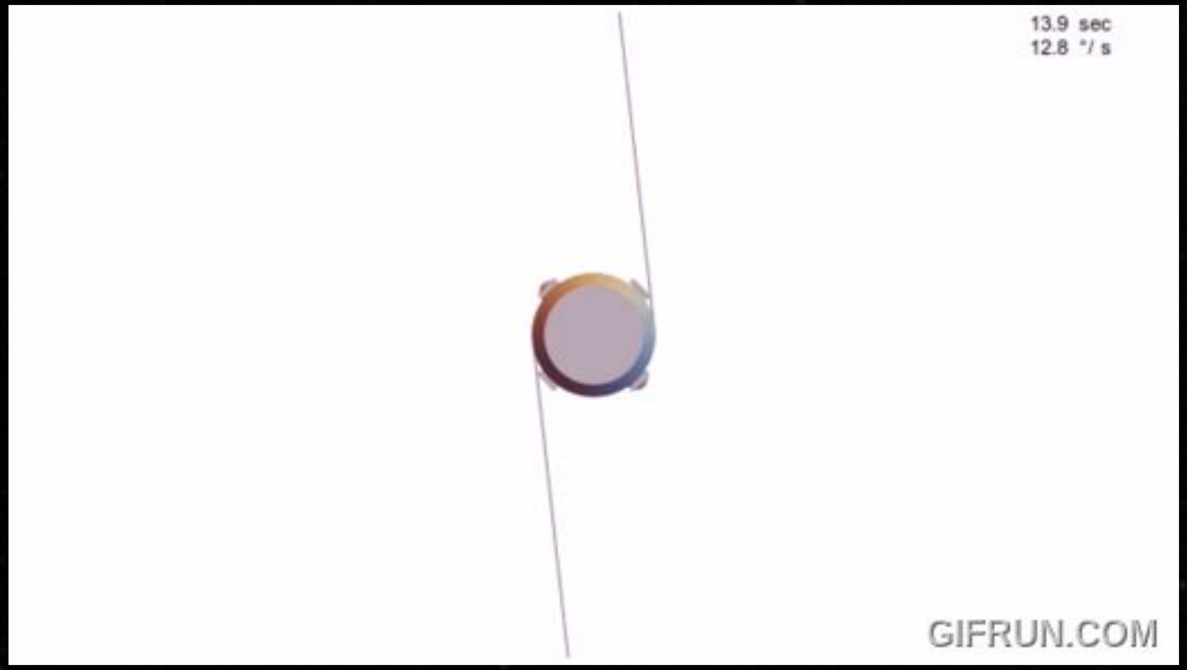
- Greatest Disturbance Torque:
  - Gravity Gradient From Uranus: ~1.5*10^-9 Nm

Reaction Wheel	Maximum Torque	Mass Per Unit	Size	Operating Lifetime	Nominal Power Draw	Peak Power Draw
Rocket Lab: 60mNms	SRB Slew Rotation: ~10°/s	288g	77mm x 65mm x 38mm	5 hours	1.8 Watts	60 Watts

- Attitude Sensors:
  - 2 Star Trackers
  - 3 Axis IMU
  - 3 Axis Accelerometer
- Spin Up: [TBR]
- Spin Down: Yo-Yo Desaturation



Rocket Lab Reaction Wheel



Yo-Yo Desaturation Simulation

TT&C Requirements

TT&C subsystem shall:

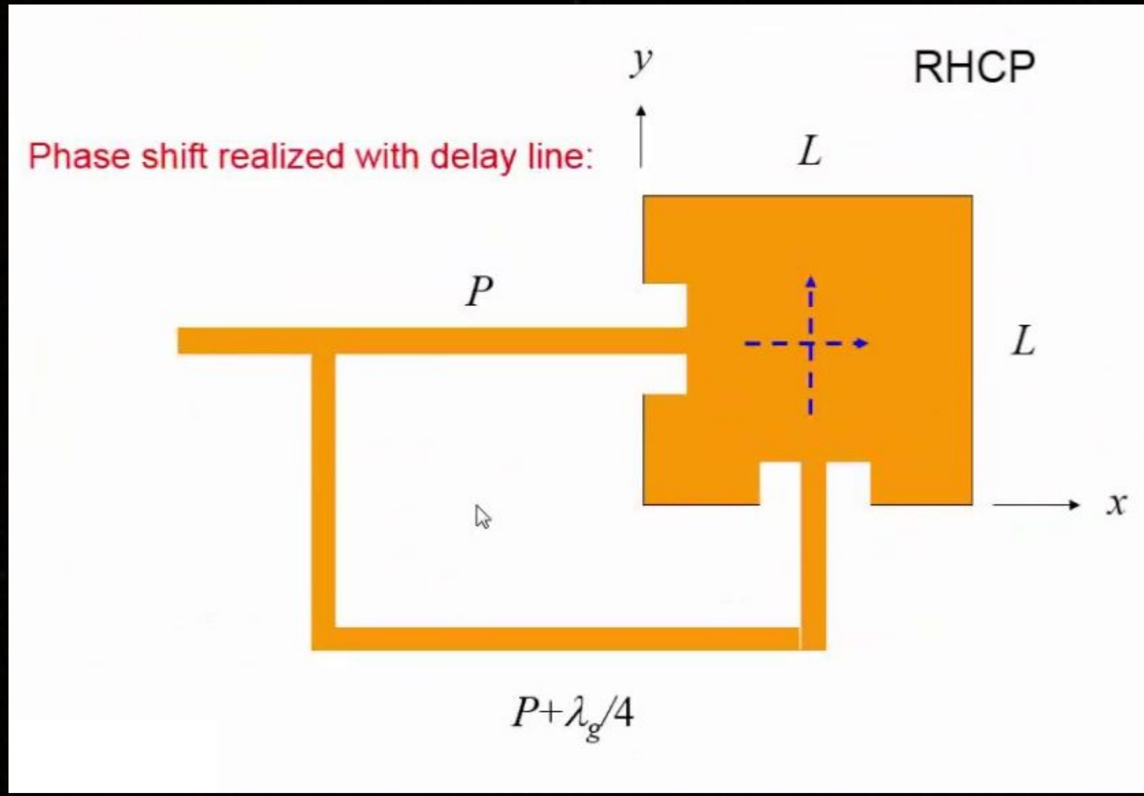
- Transmit data at a rate fast enough to complete transfer during orbiter overhead pass
- Operate at a frequency optimal for probe size and environment
  - Constrained by probe surface area, orbiter frequency capability, surface composition

TT&C subsystem should:

- Survive and be operational during and following impact

TT&C

- Antenna Design: Patch w/ integrated polarization
  - No moving/deployable parts necessary
  - 6dBi Gain
- Optimal Frequency: 2GHz (low-S-band)
  - 15cm wavelength takes advantage of maximal exposed rear-facing surface area
  - Low S-band allows penetration of ice if antenna is covered
  - Ice attenuation: 0.05-0.6 dB/m depending on composition (vs 65dB/m for water)
- Link budget allows for -104dBm received power on orbiter, at 10° mismatch, -118dBm at 45°
- Data margin allows for 2.14mbps data rate using maximum margin (~1dB). 10kbps at 15dB margin



Patch antenna geometry and design

Structures Requirements

Structure subsystem shall:

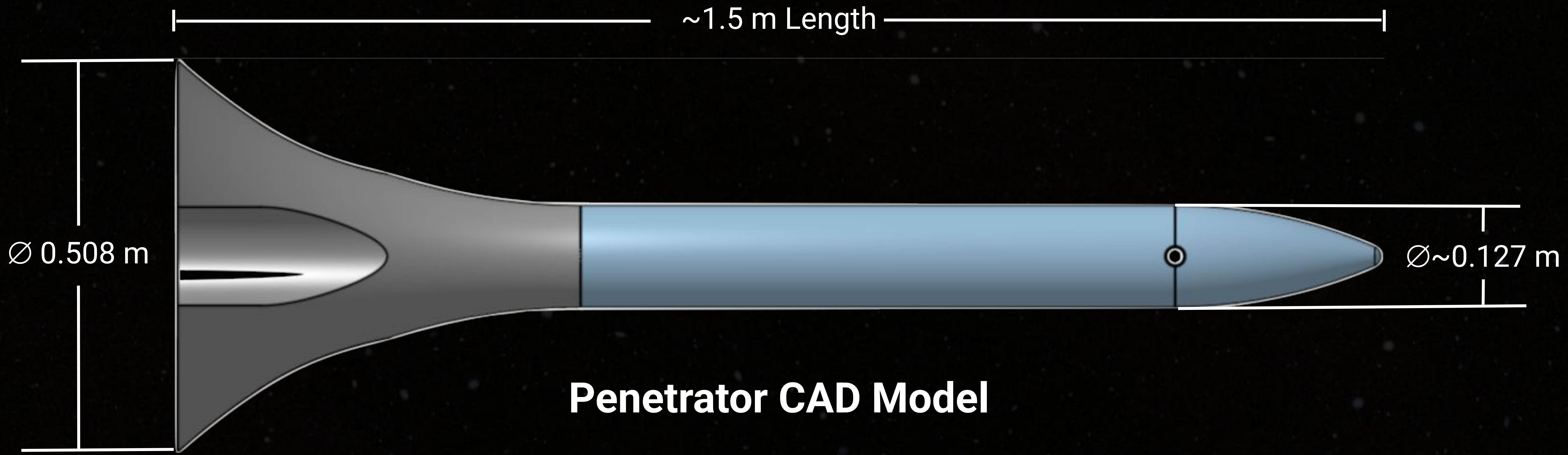
- Contain and protect all components during the launch, transit and deployment phases
- Protect all operating components during the science phase pre-impact
- Fit within the allocated payload static envelope for the launch vehicle while attached to the orbiter with [TBR] margin
- Shield the imagers from dust and other hazards during approach and descent

Structure subsystem should:

- Protect all post-impact operating components during impact

Structure: Penetrator Design

The preliminary design is for a penetrator comprised of 3 parts:



Penetrator CAD Model

Flare

- Transmitter/Receiver
- SRBs
- Material: steel (grade TBR)

Main Body

- Batteries
- Instrumentation
- ADCS
- Material: steel (grade TBR)

Nose Cone

- Instrumentation
- Material: Titanium

Structures: Impact Overview

Hand Calculations

Three models used:

1. Hypervelocity Impacts on Low-temperature ice - Late Stage Effective Energy
2. Tate-Alekseevski model - Rigid-Body Penetration
3. Spherical Cavity-Expansion Approximation - Ogival Nose Rod

Main Assumptions

- Homogenous, solid Ti penetrator impacting solid water ice
- Standard constants / coefficients for Ti-6Al-4V grade Titanium.
- Experimentally determined values for glacier ice.

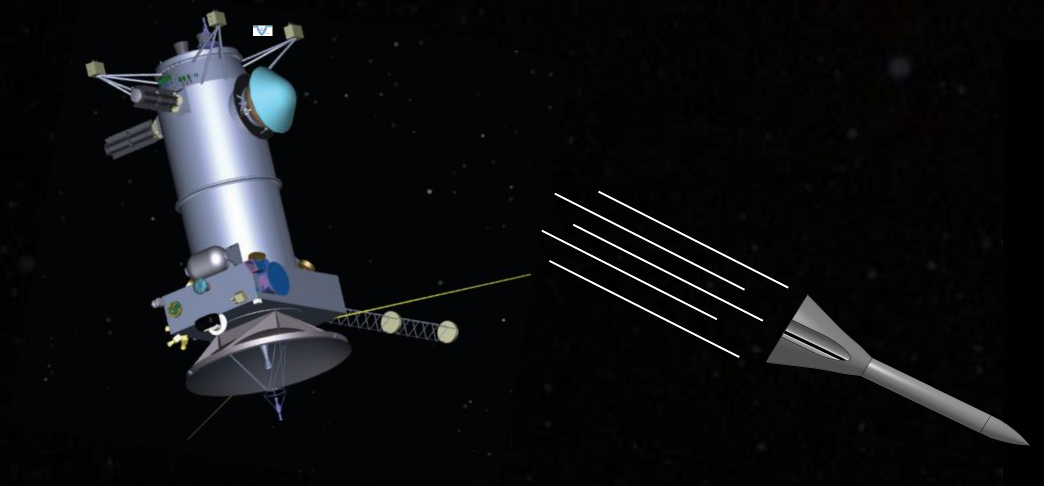
Important Dependencies

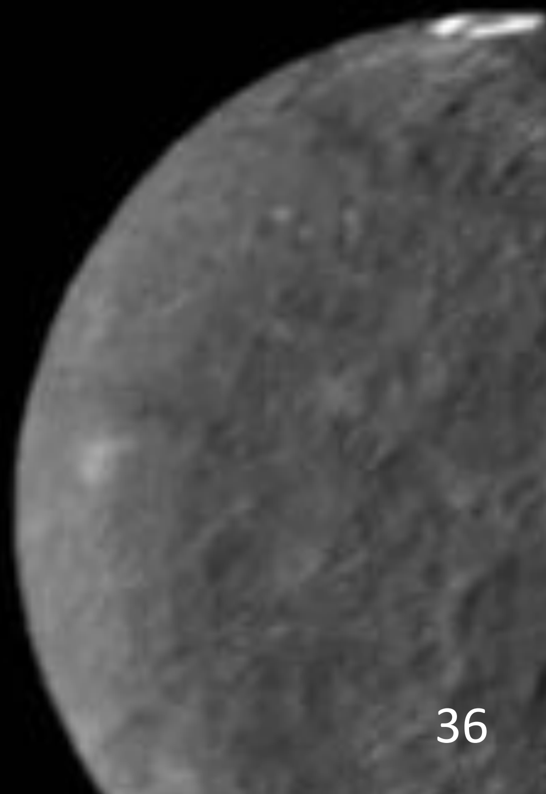
- Impact velocity
- Geometry / mass of the projectile
- Material properties of the target / projectile

Results:

- Impact force range: ~10-13MN
- Impact depth: ~3-4 m

* Not to scale





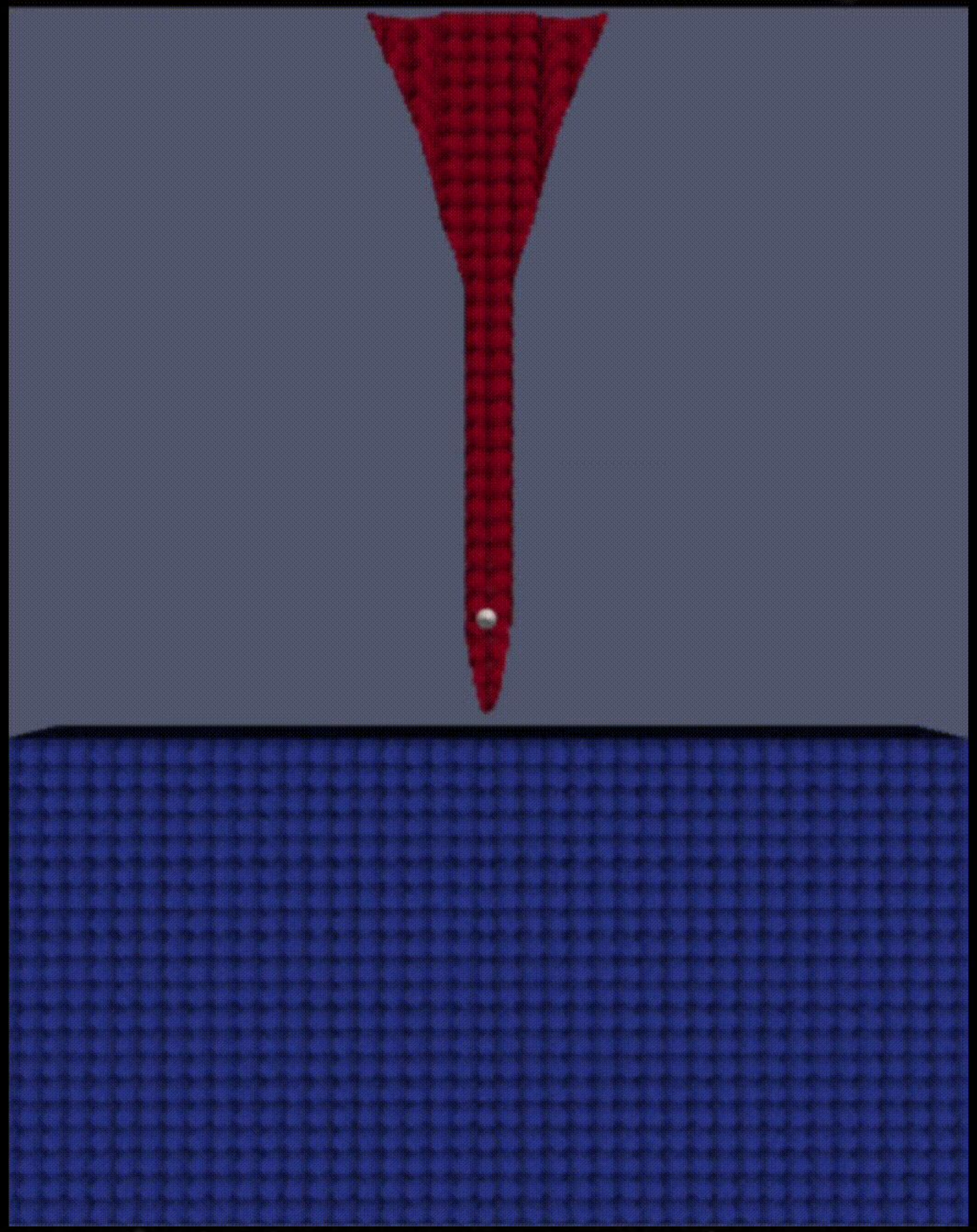
Optimal impact state

Simulation, Results, Iteration

Initial Conditions:
- Solid aluminum body: 2.8 g/cm^3
- Speed: 1 km/sec
- Impacting porous ice: 1 g/cm^3

Results and Iteration:
- Penetration depth estimation: ~3-5 meters
- Design of the following components can be done/iterated on:
  - Internal Structure:
    - Aluminum Honeycomb
  - Material Selection
    - Titanium Tip
    - High Grade Steel Body/Flare
  - Flare to Main Body Umbilical
    - Steel cables
  - Flare Separation
    - Separation Bolts
  - Flare Design Angle to Z-Axis
    - Estimated through transient FEA

Main takeaway:
- Aluminum is not a viable structural material



High-Velocity Ice Impact Simulation

Power Requirements

Power subsystem shall:

- Remain dormant during transit with minimal degradation
- Possess minimal risk of surface contamination in event of failure
- Possess constant current output capable of powering all science instrumentation, communications, C&DH, and heating coils
- Use TRL6+ components exclusively
- Operate at -20°C with minimal performance degradation
- Supply craft for 4.25 hr transit, and minimum 30 minute survival post-impact

Power subsystem should:

- Survive and be operational following impact

Primary Cell Trade Study Overview

- Comparison between consumer, defense, and custom-designed components
- Thermal batteries provide high power, but with drawbacks
  - Capacity
  - Heat Generation
- Traditional LTC and consumer-grade LiPo/LFP cannot handle impact conditions
- Solution: Custom designed cells from Deep Space 2 Probes
  - Tolerant of 80,000g impact
  - Sufficient capacity to power scientific instruments

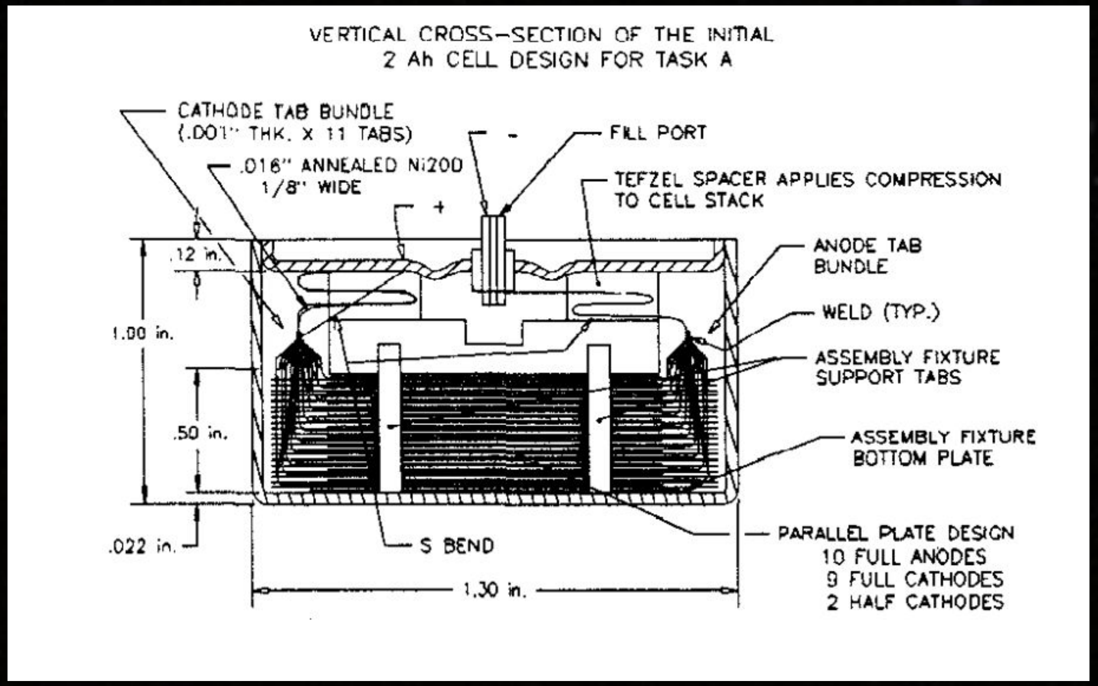
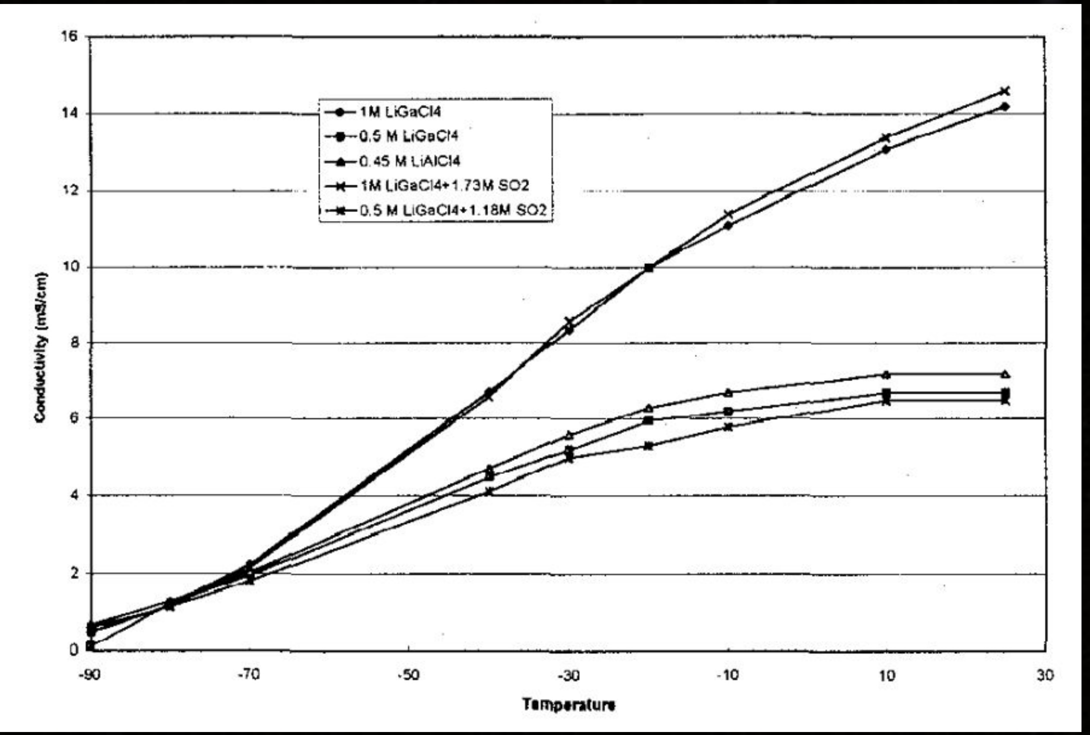


Diagram of DS2 Probe cell interior



Electrolyte comparison of DS2 cells

Primary Cell Mass/Power

- Power Required During Descent:
  - ~23W
- Power Required Post-Impact, 30 min survival:
  - ~144W
- From a pure energy density perspective, only 500g of batteries are needed
- Additional cells required to spread current load per cell out
  - 4s48p Configuration allows a safe <1A/cell at lowest voltage
- Final Mass: 4 kg
- Final Volume: 4.1 L
- 3 hr Survival

4s48p configuration for safe current distribution:	192 cells total needed
FINAL MASS (kg)	4.03
FINAL VOLUME (L)	4.14

ON DESCENT/IMPACT ONLY			
Instrument	Worst-Case Power Draw (W)	Duty Cycle	Average Power Draw (W)
Simera Sense Multispectral Imager	5	1	5
Side-View Imager	5	1	5
Uniaxial Impact Accelerometer	0.25	1	0.25
MEMS Seismometer	1.5	0.01	0.015
Temperature Probe	0.01	1	0.01
Heating Coils	140	0.04	5.6
C&DH	2	1	2
Comms	5	1	5
	TOTAL POWER DRAW (W)		23

PROLONGED MISSION ONLY			
Instrument	Worst-Case Power Draw (W)	Duty Cycle	Average Power Draw (W)
Simera Sense Multispectral Imager	5	0	0
Side-View Imager	5	0	0
Uniaxial Impact Accelerometer	0.25	0	0
MEMS Seismometer	1.5	1	1.5
Temperature Probe	0.01	1	0.01
Heating Coils	140	1	140
C&DH	2	1	2
Comms	5	0.05	0.25
	TOTAL POWER DRAW (W)		144
CELL VOLUMETRIC ENERGY DENSITY (Wh/L)			248
CELL GRAVIMETRIC ENERGY DENSITY (Wh/kg)			330
	TOTAL ENERGY (J)		608756
	TOTAL MASS (kg)		0.5
	TOTAL VOLUME (L)		0.7

C&DH Requirements

CD&H subsystem shall:

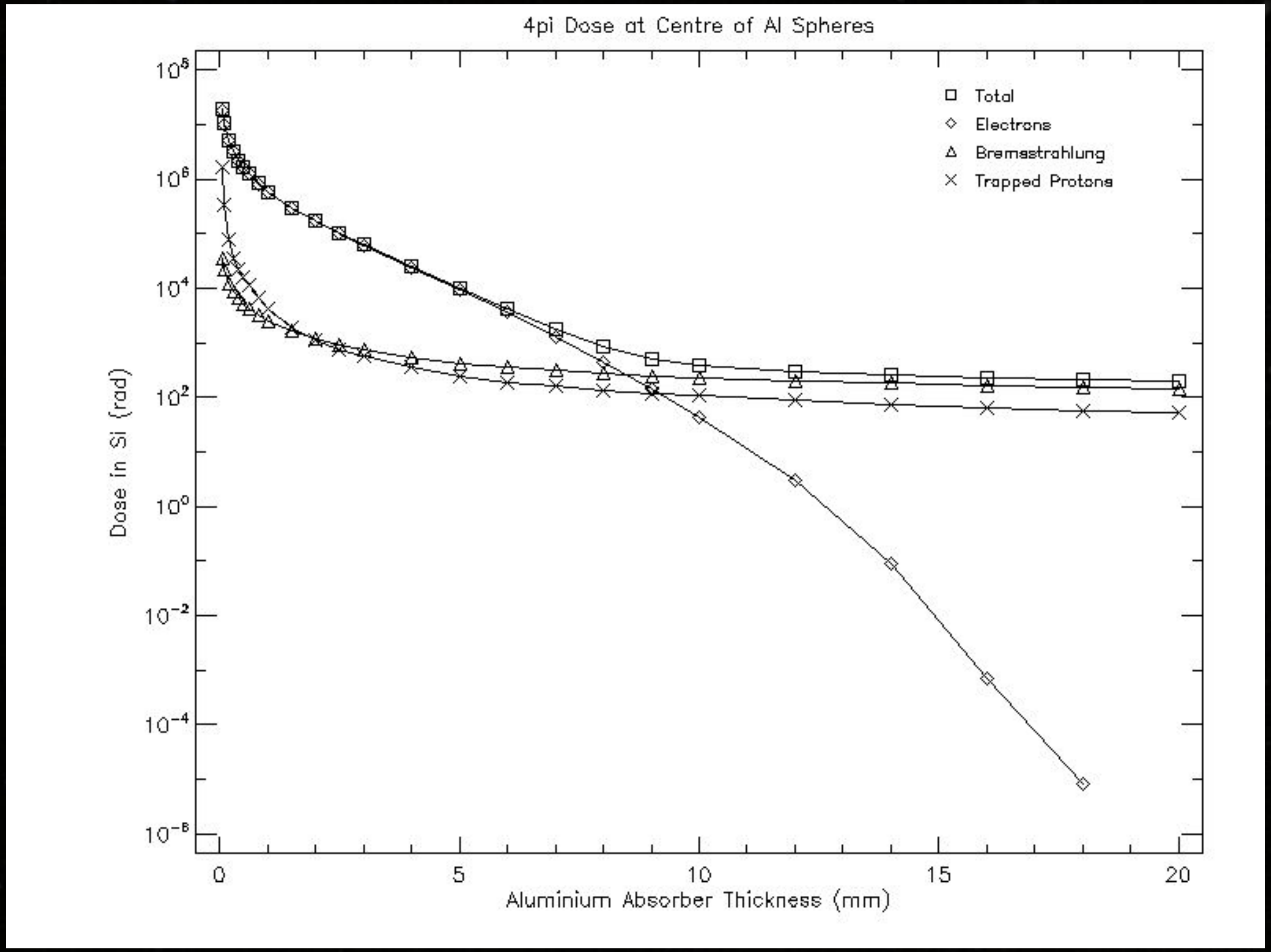
- Handle payload deployment, communication, management, and data processing
- Store and transmit data
- Withstand total radiation dose of 50 krad

CD&H subsystem should:

- Survive and be operational following impact

Radiation Effects and C&DH

- Ionizing Radiation dose upon earth departure/Van Allen traversal simulated via SPENVIS
- Approx. 10krad w/ 5mm shielding
- 1k rad w/ 10mm shielding
- With additional shielding from penetrator body and orbiter, total dose less than 30krad
  - Microchip ATmegaS128
  - 8-bit microcontroller, rad hardened version of µC line commonly used in Arduino
- Total data storage
  - 50GB



SPENVIS Ionizing radiation dose simulation near Earth

Thermal Requirements

Thermal subsystem shall:

- Maintain all components within their survival temperature limits with ±5°C margin for relevant mission modes
- Maintain all components within their operational temperature limits with ±5°C margin for relevant mission modes
- Not allow greater than [TBR] W of heat flow to/from the flagship.
- Survive and be operational following all launch and deployment environments (i.e. shock, vibe, acoustics)
- Have necessary radiation resistance to survive in all mission radiation environments
- Use COTS and TRL 6+ technology

Thermal subsystem should:

- Survive and be operational following maximum impact shock

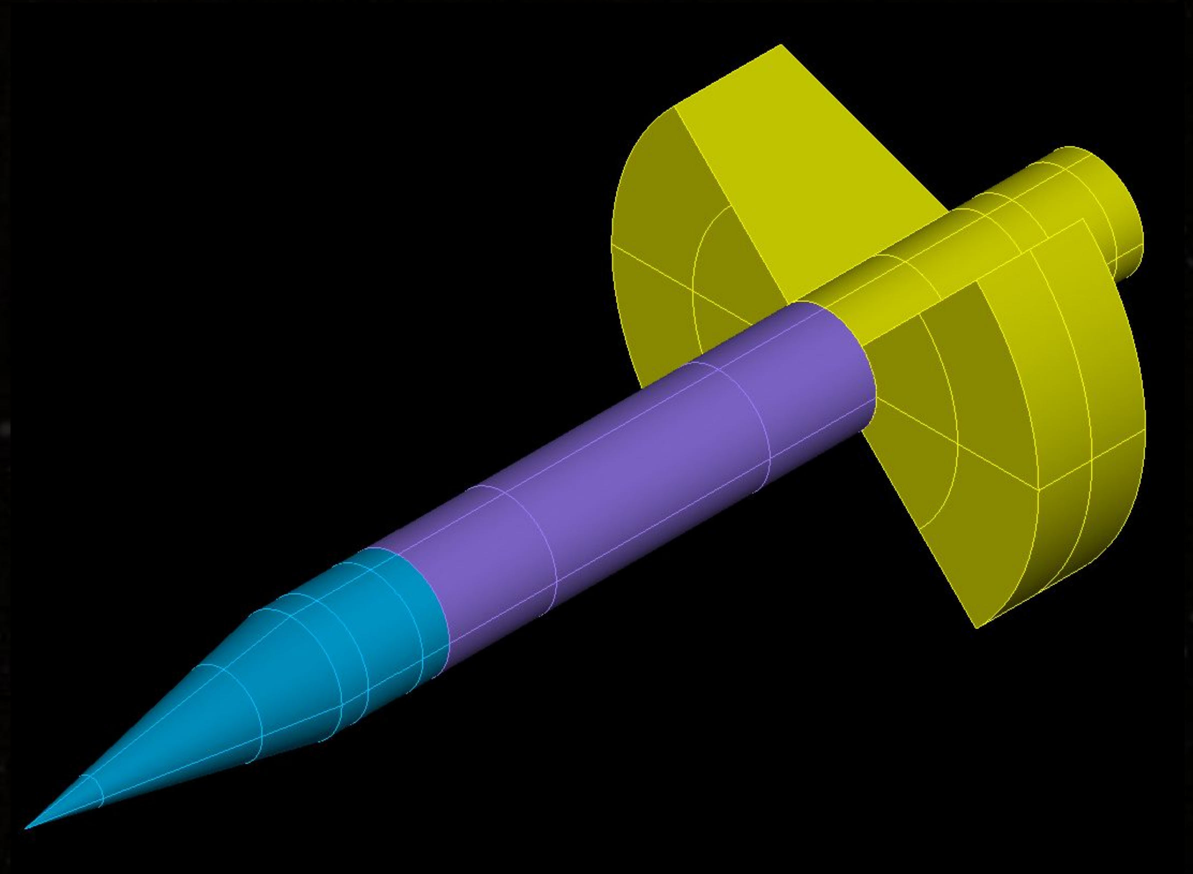
Thermal Concerns

Thermal was identified as a high risk concern for this system

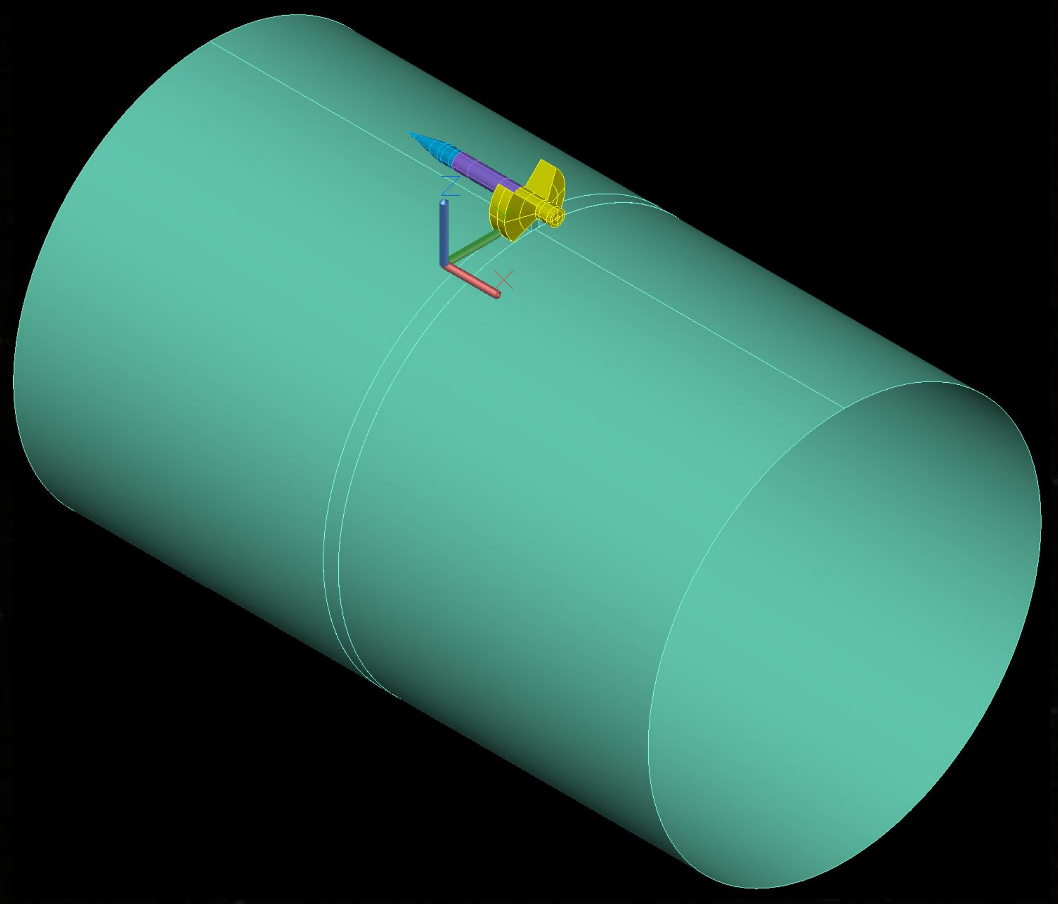
- Pre-Deployment Transit:
  - Limited power from orbiter
- Post-Deployment Transit:
  - Low environmental heating
- Post-Impact:
  - How long can components be keep operational in 30K ice?
- Multiple analyzes completed to confirm a solution is possible
  - Hot transit and orbit cases
  - Cold transit and orbit cases
  - Cold surface embedment case

Thermal Summary

- Confirmed that there is a viable thermal solution through thermal analysis
- Room for improvement on thermal design
- Lots of passive thermal control is required
- Active thermal control:
  - Up to 140 W heater power for operation modes
  - As low as <1 W heater power for survival modes

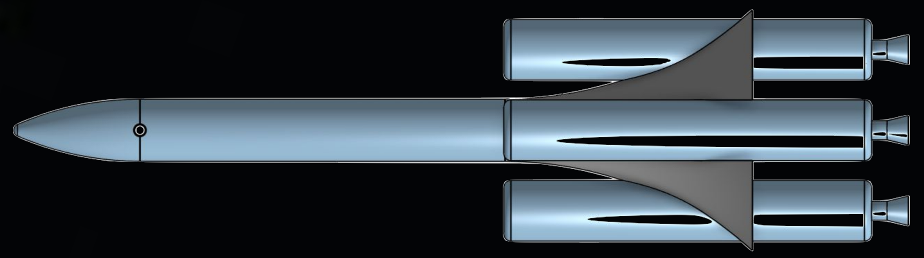


Thermal Desktop Model of Penetrator



Thermal Desktop Model of Penetrator on Orbiter

ConOps



Deployment: T-4.6 hrs

- Umbriel flyby within threshold velocity
- Target location determined

Approach: T-4.4 hrs

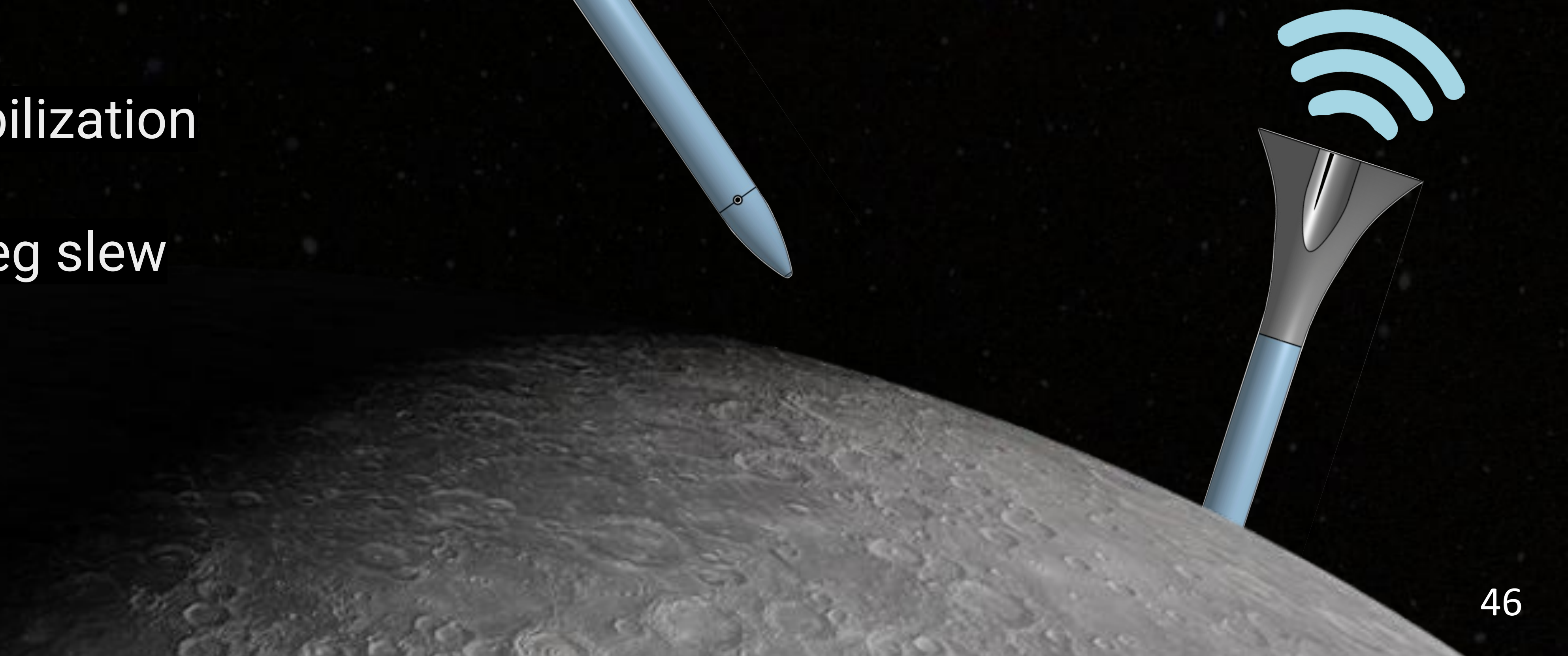
- ADCS pointing / stabilization
- ΔV Burn
- SRB jettison / 180 deg slew

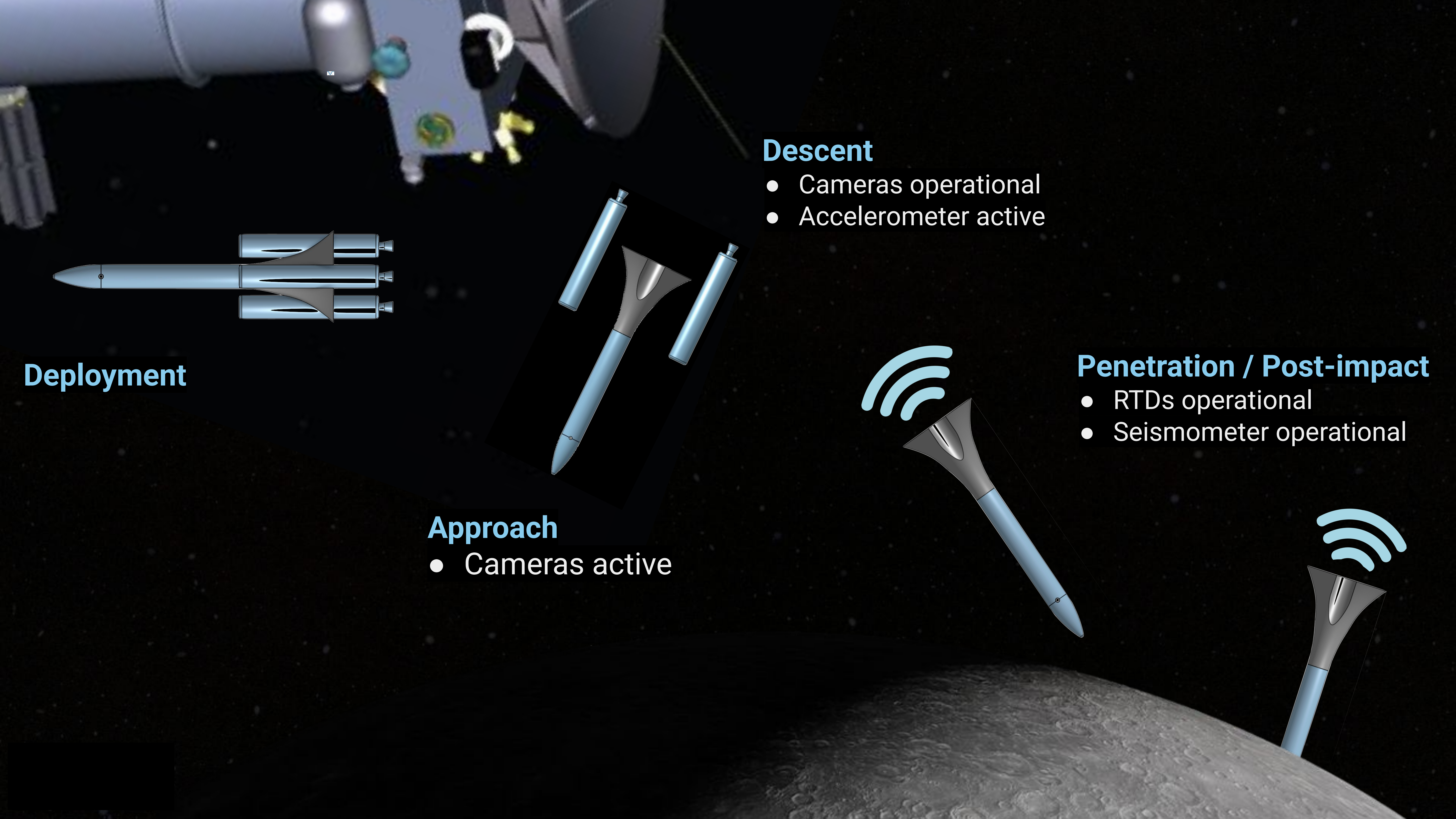
Descent: T-1 hr

- ADCS pointing / stabilization
- Imagers and accelerometer active
- Image compression / transmission

Penetration: T-0

- Thermal probe and seismometer active
- Data compression / transmission

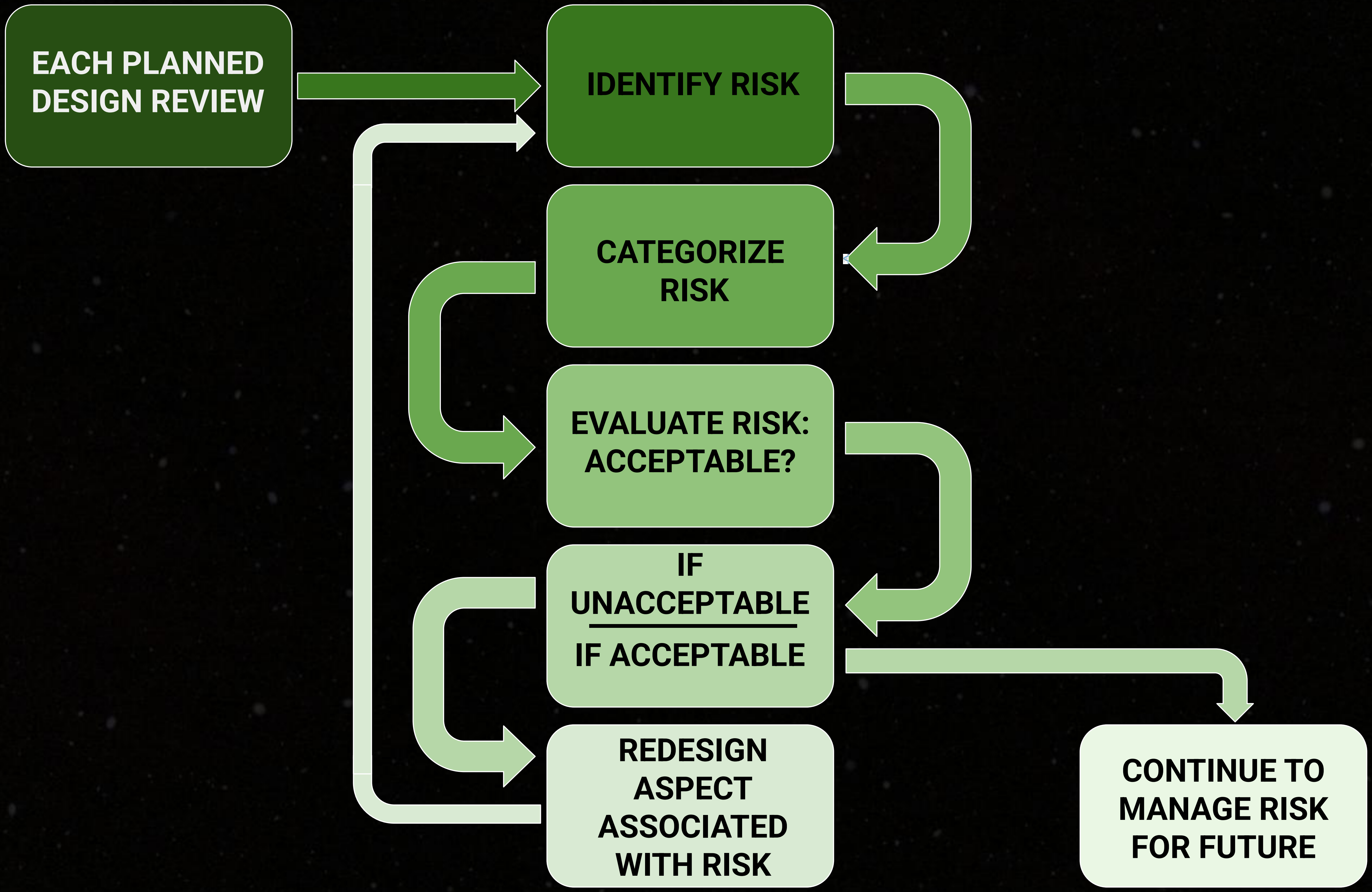




Descent
● Cameras operational
● Accelerometer active
Deployment
Penetration / Post-impact
● RTDs operational
● Seismometer operational
Approach
● Cameras active

Risk

Risk Management Plan



Risk Matrix Key

Low probability of threat occurrence, no to low severity	Members take responsibility with guidance from subteam lead
Possibile to likely occurrence, moderate to high severity	Subteam lead takes responsibility with input from members or chief engineer
Certainty of threat occurrence, catastrophic outcome	Chief engineer takes responsibility with input from subteam lead

SYS	*System*
ADG	*ADCS/GNC*
CDH	*Command & Data Handling*
COM	*Communications*
CST	*Cost*
POW	*Power*
PRP	*Propulsion*
SCI	*Science*
SHD	*Schedule*
STR	*Structures*
THR	*Thermal*

System Risk Matrix

*56 total risks

Probability x Detectability	Severity: 1 Negligible	2 Low	3 Moderate	4 High	5 Catastrophic
1-5 Very Unlikely	POW--02 POW-05	ADG-05 CDH-04	SCI-04 SCI-08 POW-01 POW-04	THR-02 ADG-03 ADG-04 STR-06 CDH-03 CDH-06 SCI-03 SHD-03 COM-01 POW-03 COM-02 STR-05 SCI-05 STR-01 PRP-02	ADG-01 ADG-02 CST-04 SCI-01 SCI-09 PRP-03 POW-06 SYS-02
6-10 Unlikely			THR-03 STR-02 CST-01 THR-05 SCI-07	PRP-05 PRP-06 SHD-04 CST-05 CST-06 THR-04 PRP-04 STR-04	CDH-01 STR-03 SCI-02 CDH-05 SHD-02 SYS-01
11-15 Possible				THR-01	PRP-01 SCI-06 SHD-01
16-20 Likely					CST-03
21-25 Certain					

System Risk Matrix - Top Risks

*4 risks with highest RPNs

Probability x Detectability		Severity: 1 Negligible	2 Low	3 Moderate	4 High	5 Catastrophic
	1-5 Very Unlikely	POW--02 POW-05	ADG-05 CDH-04	SCI-04 SCI-08 POW-01 POW-04	THR-02 ADG-03 ADG-04 STR-06 CDH-03 CDH-06 SCI-03 SHD-03 COM-01 POW-03 COM-02 STR-05 SCI-05 STR-01 PRP-02	ADG-01 ADG-02 CST-04 SCI-01 SCI-09 PRP-03 POW-06 SYS-02
	6-10 Unlikely			THR-03 STR-02 CST-01 THR-05 SCI-07	PRP-05 PRP-06 SHD-04 CST-05 CST-06 THR-04 PRP-04 STR-04	CDH-01 STR-03 SCI-02 CDH-05 SHD-02 SYS-01
	11-15 Possible				THR-01	PRP-01 SCI-06 SHD-01
	16-20 Likely					CST-03
	21-25 Certain					

Top Risks Mitigation Plan

*utilized FMEA from HW5

FMEA Reference #	Part & Failure Mode	RPN Score	Mitigation Plan	Goal RPN
CST-03	Initial cost estimates inaccurate -> budget overruns	80	• Perform detailed cost estimations • Build a historical cost model • Track high-variance items and assumptions	45
SHD-01	Vendors fail to provide components on time -> schedule overrun	75	• Initiate early vendor communication • Identify potential delays early • Make scheduling issues more detectable	30
SCI-06	Instruments don't turn on -> faulty equipment/connections	60	• Conduct early integration testing • Use engineering models (thermal, vibration, electrical)	30
PRP-01	Impact trajectory compromised -> insufficient delta V	60	• Add margin to SRB delta-V capacity • Run higher-fidelity trajectory analysis • Refine mass budget to improve delta-V estimates	30

Goal Risk Matrix

*4 top risks mitigated

Probability x Detectability	Severity: 1 Negligible	2 Low	3 Moderate	4 High	5 Catastrophic
1-5 Very Unlikely	POW--02 POW-05	ADG-05 CDH-04	SCI-04 SCI-08 POW-01 POW-04 PRP-06 SHD-04 THR-03	THR-02 ADG-03 ADG-04 STR-06 CDH-03 CDH-06 SCI-03 SHD-03 COM-01 POW-03 COM-02 STR-05 SCI-05 STR-01 PRP-02	ADG-01 ADG-02 CST-04 SCI-01 SCI-09 STR-03 PRP-03 POW-06 SYS-02 SCI-02 CDH-05
6-10 Unlikely			STR-02 CST-01 THR-05 SCI-07	PRP-05 THR-01 CST-05 CST-06 THR-04 PRP-04 STR-04	CDH-01 PRP-01 SHD-02 SYS-01 SCI-06 SHD-01 CST-03
11-15 Possible					
16-20 Likely					
21-25 Certain					

Budgets

Cost Budget

Maximum Budget: **$55 Million**

- Affirmed by mentors
- Derived from SIMPLEx
  - Small Innovative Missions for Planetary Exploration (SIMPLEx) program
  - Supports low-cost, small spacecraft missions

Detailed analysis premature at this stage

- Instrument selection finalized last week
- Structures material selection in progress
- Labor cost analysis currently infeasible due to mission uncertainties

Cost identified as a major risk due to current ambiguity

- Steve agreed based on his experience with similar mission
- Wish we could give you concrete numbers Mojtaba :(

Mass and Volume Budget

Subsystem	Mass [kg]	Allocation %	Volume [cm³]	Allocation %
Payload	9	6%	3,200	4%
Propulsion	40	25%	37,000	52%
Structures	90	58%	25,000	35%
Power	5	3%	4,140	6%
C&DH	2	1%	~150	.2%
TT&C	4	3%	~400	.6%
ADCS	4	3%	1,300	2%
Thermal	5	3%	~500	.7%
Total	**159**	**100%**	**71,690**	**100%**
Margin	**21**	**12%**	**348,310**	**83%**

Power Budget

Subsystem	Average Power [W]	Allocation %
Payload	3	9%
Propulsion	1	3%
Structures	0	0%
Power	1	3%
C&DH	2	5%
TT&C	7	19%
ADCS	2	5%
Thermal	21	57%
Total	**37**	**100%**

Link Budget - Worst Case

Item	Value	Units
Transmitter Power	5	W
Transmitter Diameter	0.107	m
Propagation Path Length	5338	km
Data Rate	1.3	kbps
Bandwidth	20	MHz
Carrier-to-Noise	62.2	dB
Link Margin	12.6	dB
Received Power	-122	dBm
Power Margin (>-137dBm)	24	dB
Exceeds Shannon Limit?	No	

Link Budget - Realistic Case

Item	Value	Units
Transmitter Power	5	W
Transmitter Diameter	0.107	m
Propagation Path Length	5338	km
Data Rate	9.41 (2Mbps in transit)	kbps
Bandwidth	20	MHz
Carrier-to-Noise	73.6	dB
Link Margin	24	dB
Received Power	-104	dBm
Power Margin (>-137dBm)	32.7	dB
Exceeds Shannon Limit?	No	

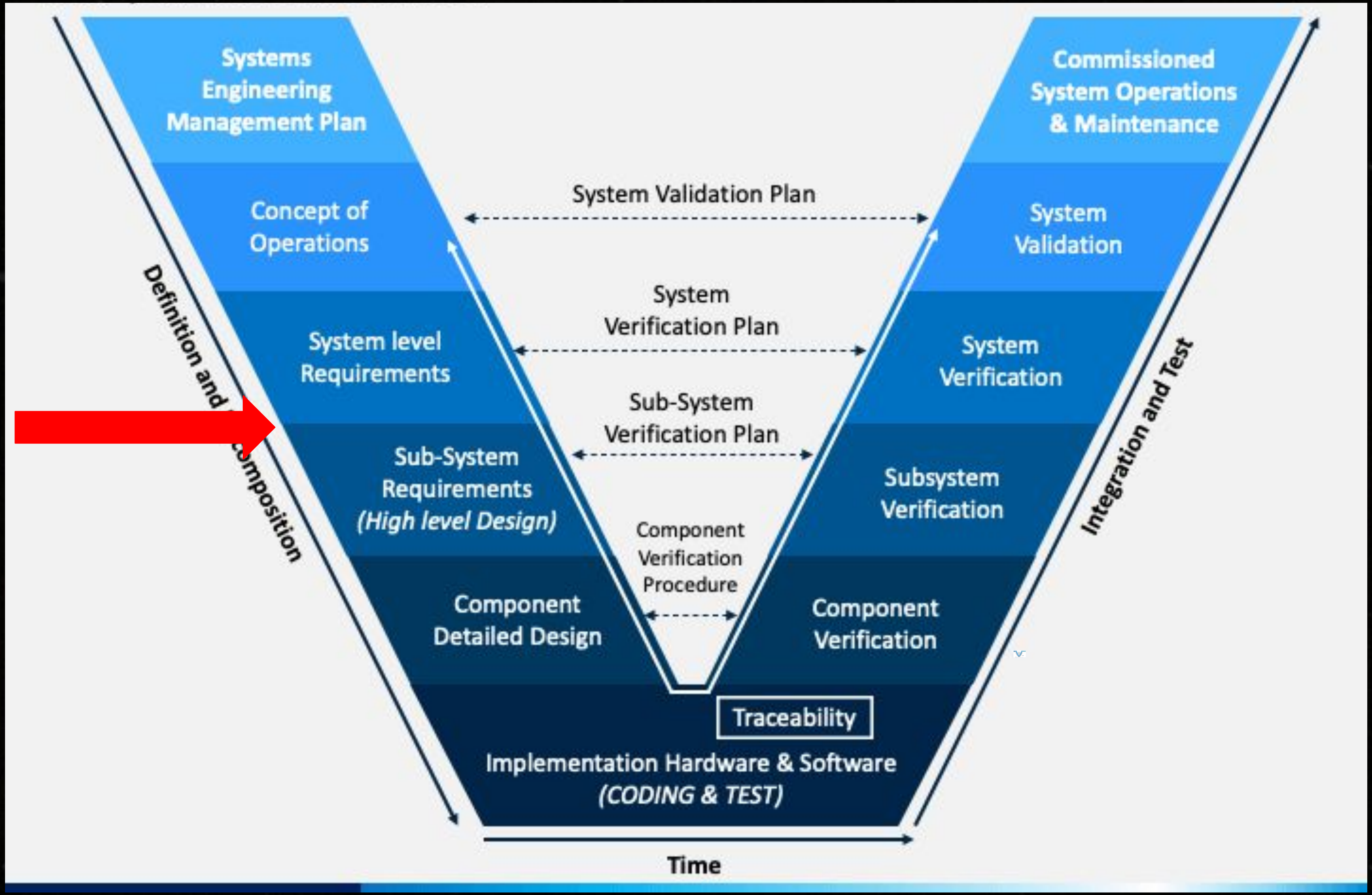
Schedule

Schedule

WBS #	TASK TITLE	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	+
1	Determine customer needs									
2	Literature review and develop STMs									
3	Develop mission concept and alts									
4	Feasibility Study									
5	Concept Selection									
6	System-level Reqs.									
7	Concept Decision									
8	Concept Development									
9	Subsystem-level Req. Flowdown									
10	In-depth Subsystem Design & Analysis									
11	Final Documentation									
12	Scientific Paper									

Systems Engineering V

We are here



Future Work

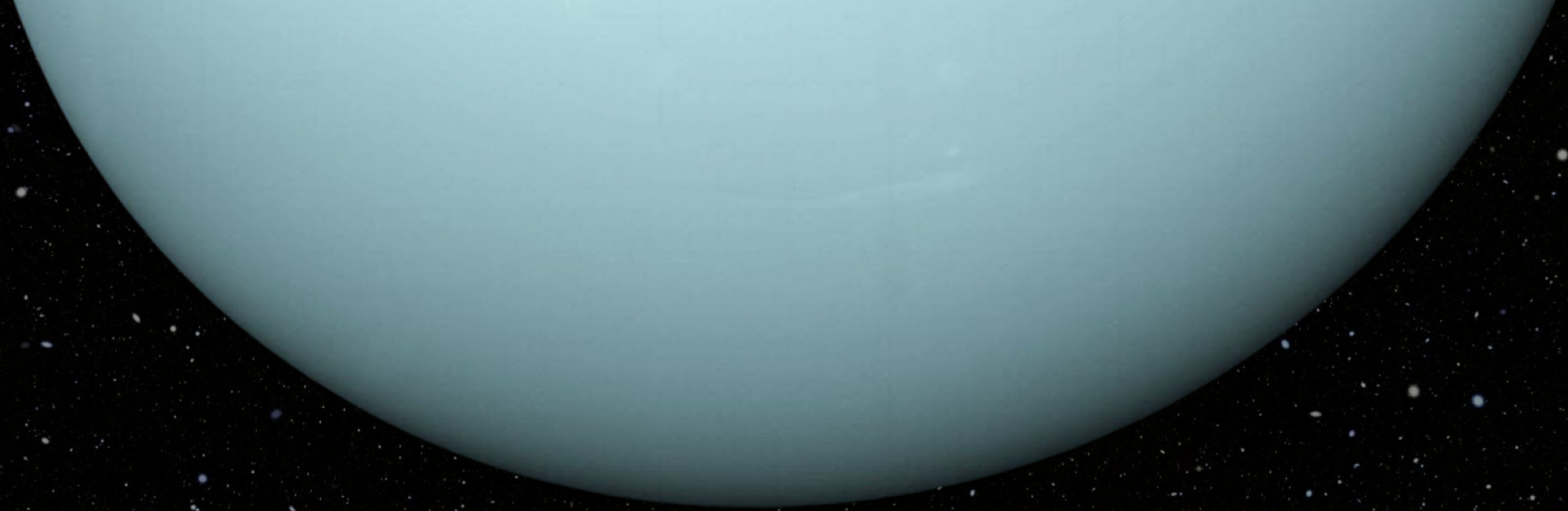
- Detailed CAD of the spacecraft
  - Stress calculations to determine flare, main body, and nose cone interfaces
  - Component placement optimization
- Determine flare and main body material
- Perform shock analysis
- Design general impactor/penetrator payload architecture with UOP design as case study
- Write conference paper

Conclusion

Goal: Design secondary mission to enhance science return of UOP flagship

Accomplished:

- Developed a penetrator concept
- Determined science and instruments to obtain unique data
  - Closeup images of surface
  - Surface hardness
  - Thermal properties
  - Seismic data post impact
- Conducted many analyses to determine survivability
- Finalised mission concept that would enhance science return of UOP



Thank You

Questions?

Backup Slides

Useful Links

- WBS
- Critical Path
- Concept Selection Trade Study
- IMS
- Requirements
- STM

STM/Science Backup Slides

Ex: Recommendations → Functional Requirements

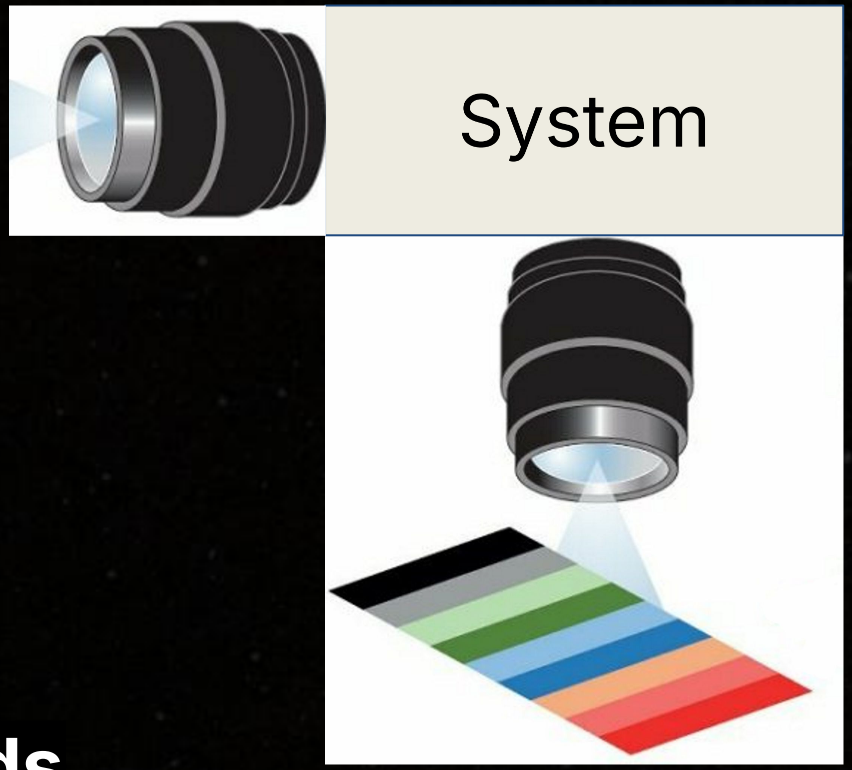
Decadal Survey Recommendation	Science Goals	Scientific Objectives	Measurement	Nominal Instrument	Functional Requirement
Q5.1c How Does the Presence of Porosity, Ices, Liquids, or Gases Affect the Physical (e.g., Mechanical, Thermal, Electromagnetic) Properties of the Crust? Q12.8a What Can Observations of Circumplanetary Material Reveal About the Formation and Evolution of Circumplanetary Systems?	Determine chemical composition of the moon's surface.	Quantify key chemical elements and minerals in the satellite's impact plume (Expected Species: H_2O, CO_2, CH_4, N_2, Carbonaceous Chondrites).	Vis Spectroscopy (remote sensing, between 1.4 - 3 um) Imaging of impact flash	Vis/NIR Imaging Spectrometer & WAC (Lucy L'Ralph) (Note - This will be on main orbiter)	The spacecraft shall maintain line of sight with the orbiter during its impact.
	Measure impact site physical properties on the large moon.	Determine surface hardness of the Uranian moons	Crater size at impact site of penetrators and impactors		The spacecraft shall create a crater with radius 3-15 meters for the flagship mission to image
Q4.4b What Materials Ejected from Impact Craters Are Deposited on Planetary Surfaces?	Observe the trajectories of ejecta from ice moon impacts	Observe the impact on the moon's surface Calculate ejecta percentages: surface return, escape, or orbit.	Surface imagery		1. The spacecraft shall impact the moon within line of sight of the orbiter 2. The spacecraft shall impact the target moon only during flybys where the orbiter's altitude is less than 500 km

Down-View Multi-Spectral & Side-View Imager

Decadal Questions:
- **Q5.1c How Does Porosity, Ices, Liquids, or Gases Affect the Physical Properties of the Crust?**
- **Q12.8a What Can Observations of Material Reveal About Formation of Circumplanetary Systems?**

Goal: **Collect surface images**
Objective: **Determine spectral composition & topography of surface**
Measurement: **Observation of surface during descent, nadir- & azimuth -facing**

Nominal Instruments:
1. **Down-view multi-spectral imager - Red, green, blue, monochrome (based on Osiris Rex Heritage)**
   a. **Resolution: [TBR] GSD at [TBR] km altitude**
   b. **Swath: [TBR] km**
2. **Side-view imager Red, green, blue, monochrome**



Functional Requirement:
1. **Down-/side-view imager shall capture surface images every [TBR] seconds**
2. **Spacecraft shall shield imager from environment & vibrations on descent**

ADCS Design

- Disturbance torques: Solar radiation, atmospheric drag, and magnetic field can be neglected because
  - solar radiation is TINY bc sun far
  - none of the moons have an atmosphere and the COP will be behind of the COM
  - The moons do not have a magnetic field and is far enough away from Uranus where its magnetic field should have very minimal to no effect on the spacecraft
  - Gravity gradient will have the largest effect due to Uranus perturbations
    - 5.79394*10^15 m^3/s^2
    - R= closest approach of moon to Uranus: Miranda @130000km
    - Theta= Local Vertical and principle Z axis
- Minimum Slew Rate: Greatest torque on the spacecraft will be from SRB ejection. Sizing in the case of ejection mishaps:
- Equations: $T_g = \frac{3\mu}{2R^3}\left|I_z - I_y\right|\sin(2\theta)$
- Trade study control and determination system: reaction control winner!
- Sensors:
  - 2 Star Trackers
    - 1 on each side of S/C

Vis/NIR Imaging Spectrometer & WAC (Lucy L'Ralph)

Decadal Questions:

- Q5.1c How Does the Presence of Porosity, Ices, Liquids, or Gases Affect the Physical (e.g., Mechanical, Thermal, Electromagnetic) Properties of the Crust?
- Q4.4b What Materials Ejected from Impact Craters Are Deposited on Planetary Surfaces?

Goals:

- Determine moon surface chemical composition
- Measure physical properties of impact site
- Observe distribution of ejecta from ice moon impacts on subsequent flybys

Objective:

- Quantify key chemical elements & minerals in satellite's impact plume
  - Species: H_2O, CO_2, CH_4, NH_3, Carbonaceous Chondrites
- Determine surface hardness of Uranian moons
- Observe impact on moon's surface
- Calculate ejecta percentages:
  - surface return, escape, or orbit

Measurement: **Imagery & spectrography (res: 250 urad/px - between 1.4 - 3 um)**

Nominal Instrument: **Orbiter Vis/NIR Spectrometer and WAC**

Functional Requirements:

1. Spacecraft shall impact the target moon within line of sight of the orbiter

Uniaxial Impact Accelerometer

Decadal Question:

- **Q5.1c How Does the Presence of Porosity, Ices, Liquids, or Gases Affect the Physical (e.g., Mechanical, Thermal, Electromagnetic) Properties of the Crust?**

Goal: **Determine the physical properties of the large moon's surface at the point of impact**
Objective: **Determine the surface hardness of the target Uranian moon**
Measurement: **Deceleration profile during impact**

Nominal Instrument: **Uniaxial Impact Accelerometer**

Functional Requirement:

1. **Uniaxial Impact Accelerometer shall record data at [TBR] readings/sec to detect the exact moment of impact and the subsequent deceleration profile**

CLASP | JPL

MEMS Seismometer

Decadal Question:

- **Q5.1a How Much Variability in Composition and Internal Structure Is There Within and Between Solid Bodies, and How Did Such Variability Arise and Evolve?**

Goal: **Probe the interior of the target Uranian satellite**

Objectives:

- **Determine the interior composition and structure of the Uranian satellite**
- **Determine the thickness of the ice sheet of target Uranian moon**

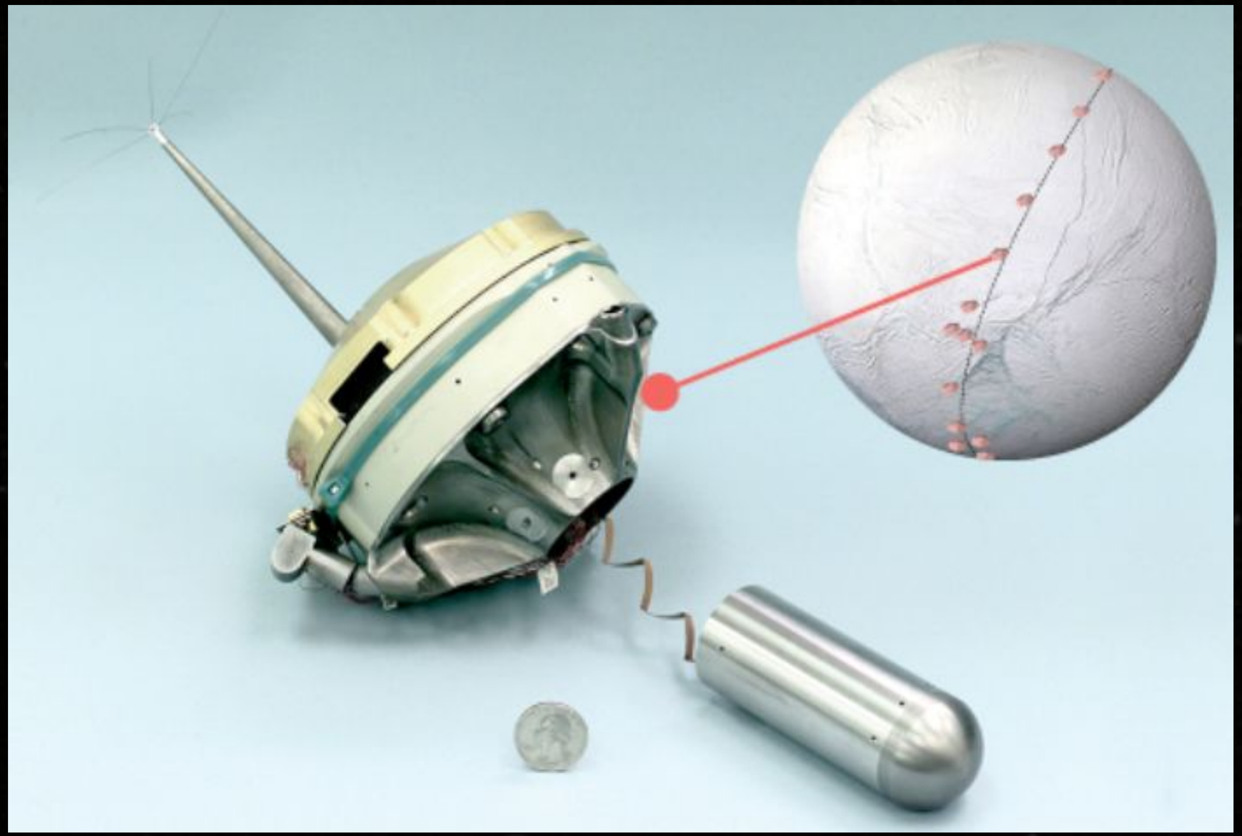
Measurement:

- **Seismic activity after impact within XX sensitivity**
- **Coda of Body waves, harmonic frequency (XX) of Crary wave**

Nominal Instrument: **MEMS Seismometer**

Functional Requirements:

1. **MEMS Seismometer shall survive expected impact forces**
2. **MEMS Seismometer shall have [TBR] signal to noise ratio**



JPL Microdevices Laboratory: High Shock Resistant Seismometer for Penetrator Concepts

CLASP | JPL

Germanium RTDs

Decadal Questions:
- **Q8.2f How Are Heat and Material Transported Through—and Ultimately Out of—Satellite Interiors?**
- **Q5.1a How Much Variability in Composition and Internal Structure Is There Within and Between Solid Bodies, and How Did Such Variability Arise and Evolve?**

Goal: **Determine the thermal properties of the moon's surface**
Objective: **Infer thermal conductivity and heat dissipation rates across the surface of the moon**

Measurements:
1. **Measure post-impact temperature decay in regolith**
2. **Compare temperature profiles at different depths (2) within the impactor**

Nominal Instrument: **Germanium RTDs**

Functional Requirements:
1. **RTD shall survive expected impact forces**
2. **RTD shall remain operational in low temperatures**
3. **RTD shall take high-frequency temperature readings post-impact**
4. **RTD shall delve at least X meters into the surface of the satellite**

Concept Selection

Explored Concepts

One Penetrator

- Survive impact to one moon; displace regolith, form crater for flagship to image, and record data on the surface

Penetrator + Impactors

- Penetrator survives impact to one moon and records data on the surface; on future flybys, drop impactors and collect seismic data from collisions

Multiple Impactors

- Impact multiple moons; displace regolith and form craters and for flagship to image

Orbiter

- Use secondary orbiter to collect additional, higher resolution science data on moons or rings

Explored Concepts Trade Study

- Conducted trade study to assess mission concept
- Selected: **1 penetrator**, highest valued concept

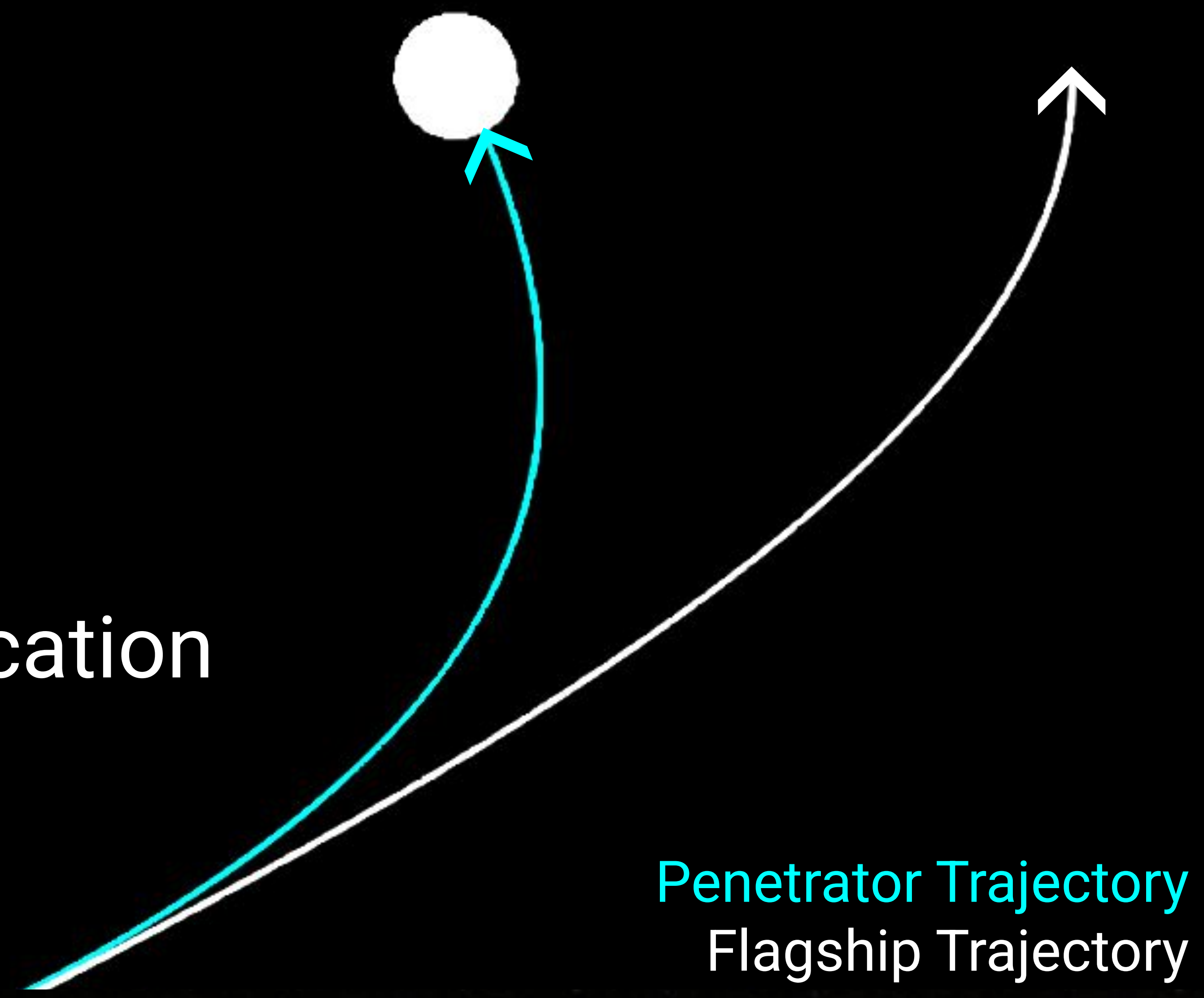
Criteria			Concepts							
			1 Penetrator		Penetrator + Impactors		Multiple Impactors		Orbiter	
Must Haves	Shall have a maximum mass allocation of 180 kg		Yes		Yes		Yes		Yes	
Must Haves	Shall have a maximum volume allocation of 1.19 m^3		Yes		Yes		Yes		Yes	
Must Haves	Provide novel science return to flagship mission		Yes		Yes		Yes		Yes	
Must Haves	Does not exceed maximum power draw from orbiter in transit		Yes		Yes		Yes		Yes	
		Weight	Value	Score	Value	Score	Value	Score	Value	Score
Wants	Amount of science objectives achieved	10	0.9	9	1	10	0.2	2	0.5	5
Wants	Technical Complexity	9	0.5	4.5	0.3	2.7	0.8	7.2	0.7	6.3
Wants	Operational Complexity	8	0.6	4.8	0.4	3.2	0.7	5.6	0.4	3.2
Wants	Influence on orbiter	7	0.75	5.25	0.5	3.5	0.2	1.4	0.25	1.75
Wants	Lifetime to provide science	6	0.3	1.8	0.2	1.2	0.9	5.4	0.6	3.6
Wants	Opportunities to transmit data	5	0.15	0.75	0.1	0.5	0.1	0.5	0.3	1.5
Wants	Previous Heritage Missions	4	0.75	3	0.25	1	1	4	0.5	2
Wants	Number of possible targets	3	0.2	0.6	0.2	0.6	0.8	2.4	0.6	1.8
Wants	Survival potential through all mission phases	2	0.7	1.4	0.7	1.4	1	2	1	2
Total Score			31.1		24.1		30.5		27.15	

Note: Nominal values shown in table, Detailed Version

Trajectory Analysis

Trajectory Analysis Overview

- **Approximate flagship trajectory around target moons**
  - Flyby altitude and velocity
  - Gravity from moon and Uranus
- **Selecting Fly-bys**
  - Lower fly-by velocity => lower impact velocity
- **Inputs**
  - Time before closest approach =>Deployment location
  - Velocity at deployment => delta V
- **Outputs**
  - Impact velocity and angle
  - Flight duration

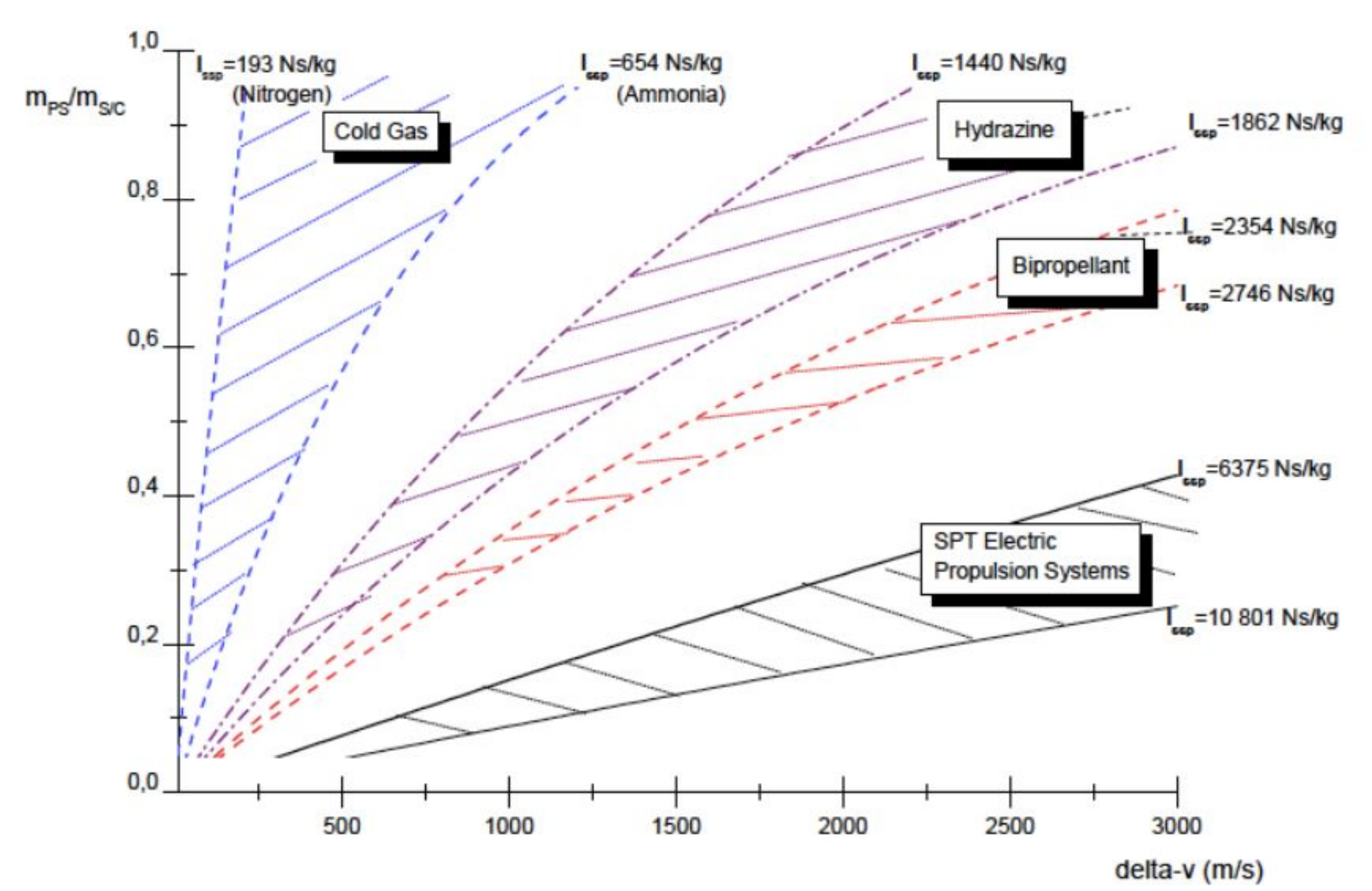


Propulsion Backup

Propulsion Overview

A trade study was done on what the best propulsion method would be. Solid Rocket propellant (SRBs) would be the best for this mission as they are:

- Inert
- Easy to start
- Will not leak propellant
- Low cost/mass/volume
- Weight can be shed for lower impact energy
- Low battery power requirement
- High thrust



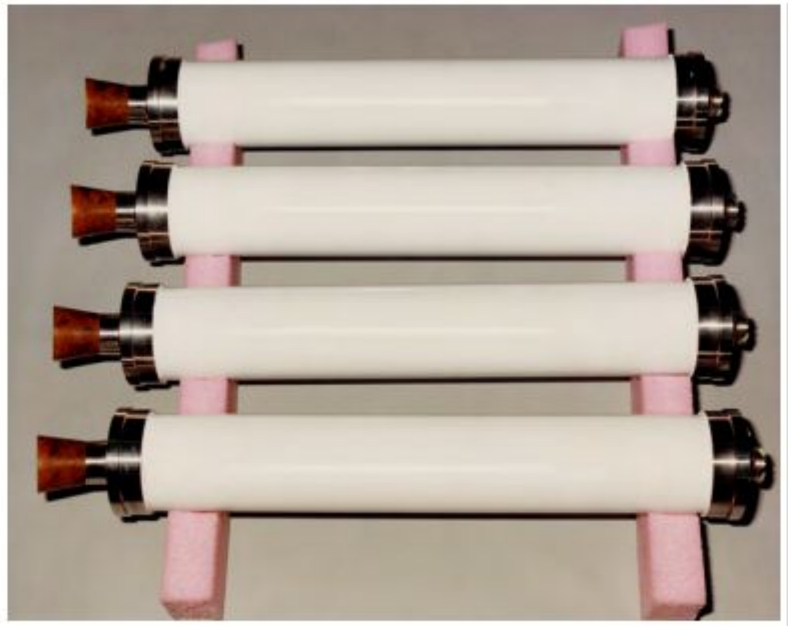
Propulsion Overview

Star 5D DeltaV calculation and initial constraints:

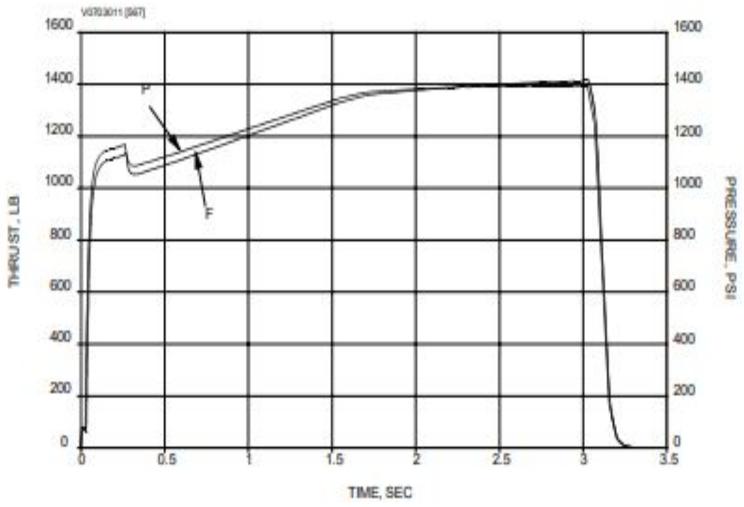
- 100kg total impactor mass w/o SRBs
- 10.23kg loaded/3.32kg empty
- ISP: 256 seconds
- g: 9.8066m/s^2

1 motor: ΔV=256∗9.8066*ln(110.23/103.32)=162.52m/s
2 motors: ΔV=305.93 m/s
3 motors: ΔV=433.59 m/s
4 motors: ΔV=548.11 m/s

ADCS thrust vectoring can be used to meet ΔV requirements for the intended trajectory.



The STAR 5D rocket motor was designed and qualified (1996) to serve as the rocket-assisted deceleration motor on the Mars Pathfinder mission for the Jet Propulsion Laboratory (JPL) in Pasadena, CA. The STAR 5D features a titanium case, head-end ignition system, and canted nozzle design and is based on earlier STAR 5 designs. Three of these motors were fired on July 4, 1997, to slow the Pathfinder spacecraft to near-zero velocity before bouncing on the surface of Mars.



MOTOR DIMENSIONS

Motor diameter, in.	4.88
Motor length, in.	32.7

MOTOR PERFORMANCE (-22°F VACUUM)

Burn time/action time, sec	3.03/3.28
Ignition delay time, sec	0.029
Burn time average chamber pressure, psia	1,299
Maximum chamber pressure, psia	1,406
Total impulse, lbf-sec	3,950
Propellant specific impulse, lbf-sec/lbm	259.5
Effective specific impulse, lbf-sec/lbm	256.0
Burn time average thrust, lbf	1251
Maximum thrust, lbf	1,410

NOZZLE

Initial throat diameter, in.	0.869
Exit diameter, in.	2.345
Expansion ratio, initial	7.3:1
Cant angle, deg	17

WEIGHTS, LBM

Total loaded	22.55
Propellant (including igniter propellant)	15.22
Case assembly	5.93
Nozzle assembly	1.40
Total inert	7.33
Burnout	7.12
Propellant mass fraction	0.68

TEMPERATURE LIMITS

Operation	-67°-158°F
Storage	-80°-172°F

PROPELLANT DESIGNATION TP-H-3062

CASE MATERIAL .... TITANIUM

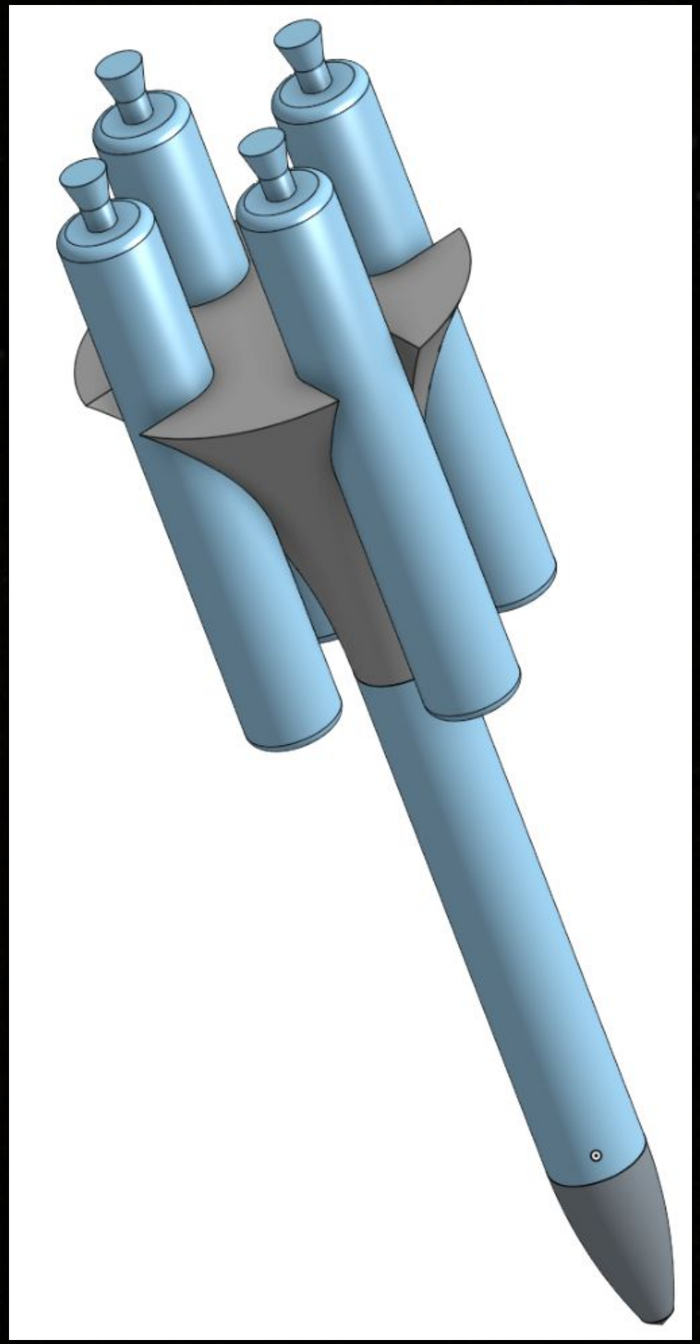
PRODUCTION STATUS .... FLIGHT-PROVEN

$$\Delta v = (v_e := I_{sp} * g_0) * \ln\left(\frac{m_0}{m_f}\right)$$

SRB Mounting/Ejection

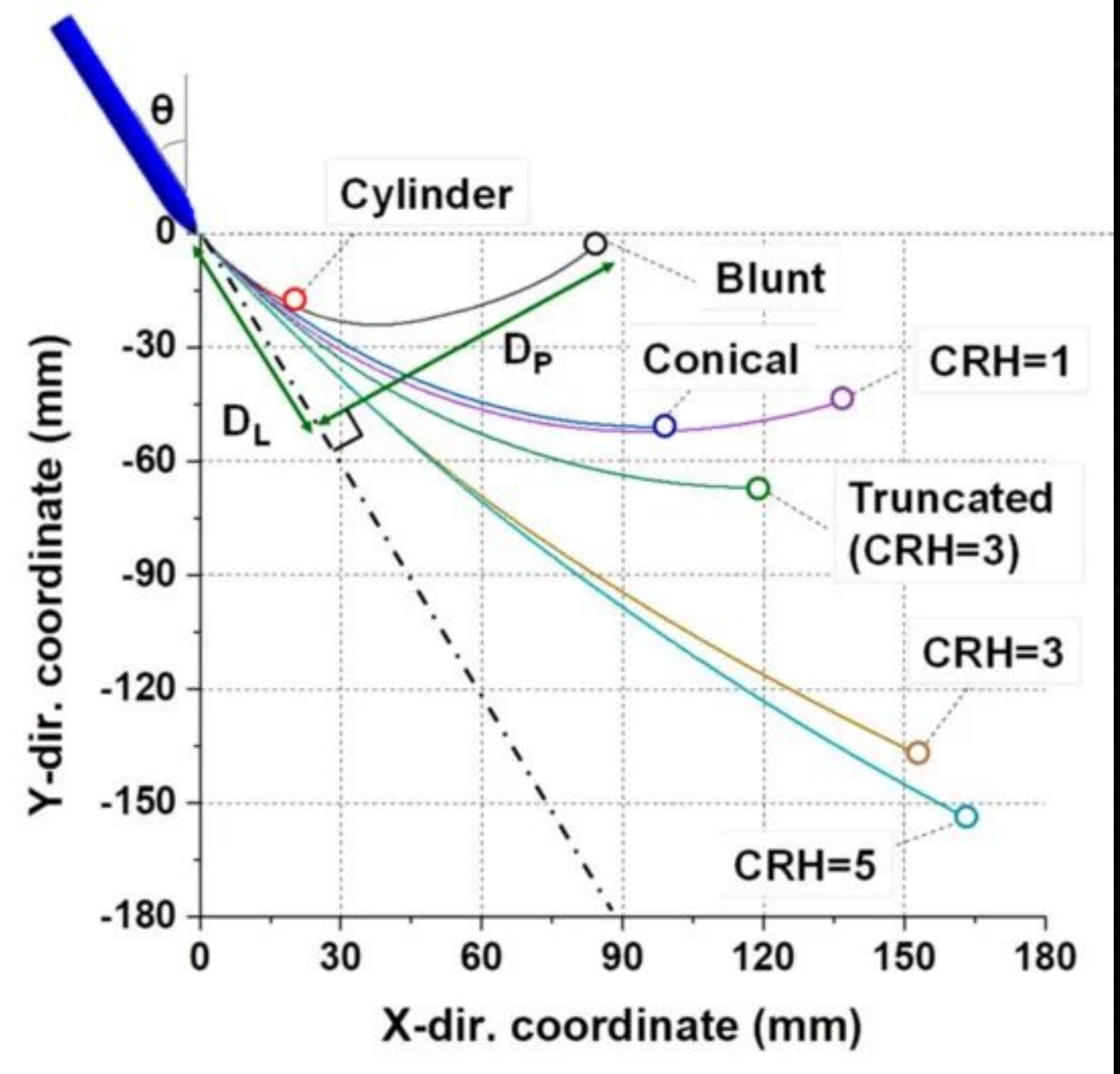
To minimize risk/potential damage to the spacecraft and ADCS fatigue/saturation

- SRBs will be mounted with the nozzles facing aft
  - Avoids the hot gasses from interfering with the main body/tip
- Staggered SRB jettison to induce a 180° rotation without ADCS
  - Allows for the tip to point in the direction of travel post SRB shutdown
  - Spring loaded ejection with burn wire trip mechanism
  - Spacecraft flip slew rate to not exceed 20°/sec (~10 seconds)



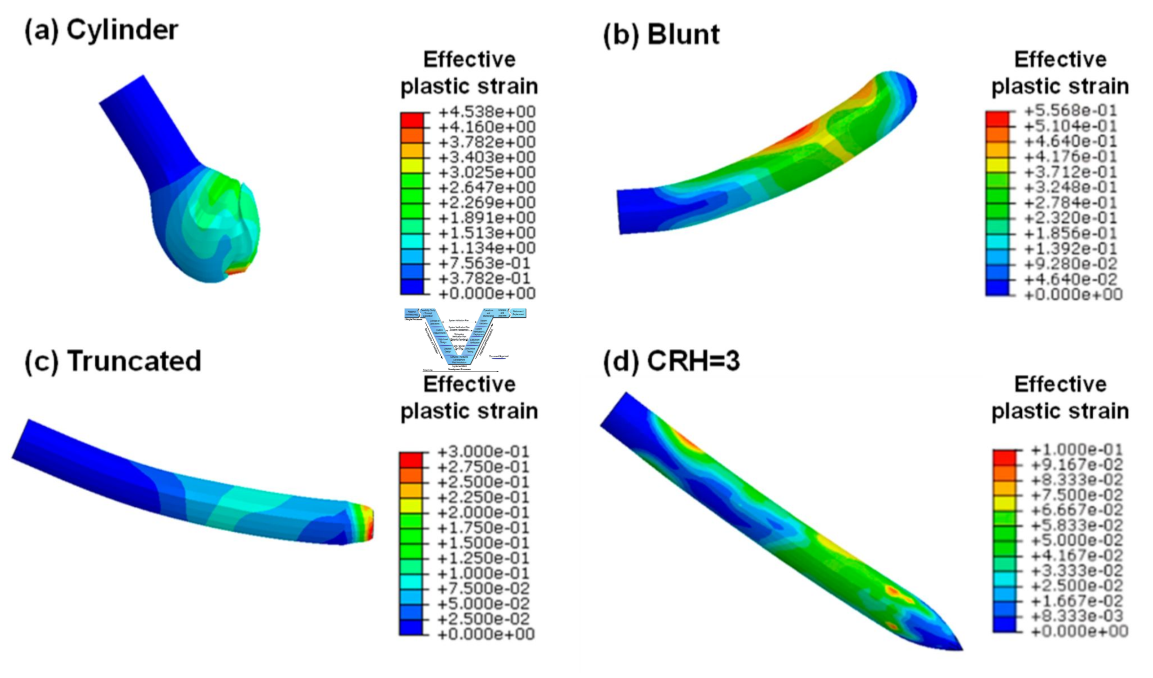
Structures Backup

Nose Cone Trade Study Overview

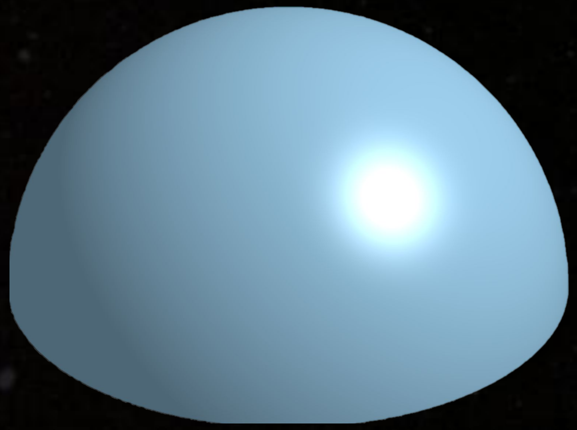


Criteria	Penetration capability, deflection angle, yaw resistance, tip strength
Relevant Requirement	STRUCT_1: The structure shall contain and protect all components during the launch, transit and deployment phases

Winner: Rounded-Tip Ogive



Option 1:
Sharp ogive



Option 2:
Hemispherical

Option 3:
Rounded tip ogive

Alternatives

*Above images taken from literature review sources, not our own calculations.

Impact Force Calculations

Criteria	Similarities to expected environment, agreement with other models, quality and number of assumptions used.
Relevant Requirement	STRUCT_1: Contain and protect all components during the launch, transit and deployment phases.

Models Used

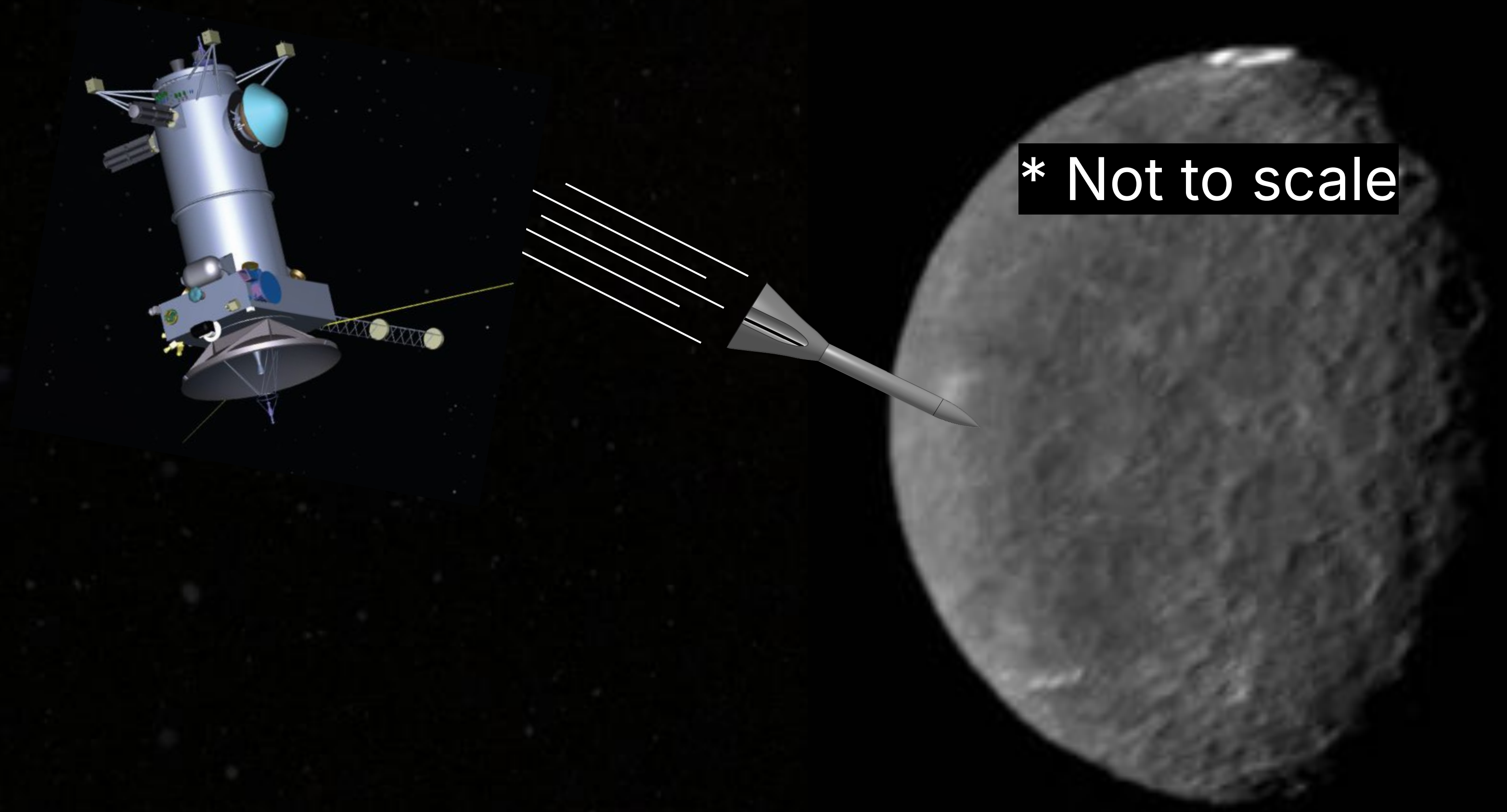
1. Hypervelocity Impacts on Low-temperature ice - Late Stage Effective Energy
2. Tate-Alekseevski model - Rigid-Body Penetration
3. Spherical Cavity-Expansion Approximation - Ogival Nose Rod

Main Assumptions

- Homogenous, solid penetrator impacting solid water ice
- Standard constants / coefficients for Ti-6Al-4V grade Titanium.
- Experimentally determined values for glacier ice.

Important Dependencies

- Impact velocity
- Geometry / mass of the projectile
- Material properties of the target / projectile



Expected force upon impact: 12.258 - 18.325 MN
Expected penetration depth: 2.709 - 3.555 m

Design Next Steps

- Import the CAD of all instruments to know internal mass/volume allocation per bay
  - Given total impact force estimation, calculate the stress on each section to find best method of attachment (brackets/welding/rivet/fasteners)
  - Optimal locations for each component
  - Nose cone/body/flare mounting method

- Finalize material selection trade study for each part

- Finish the design of the SRB ejection
  - Spring load calculations
  - Lateral force requirement and induced stress

- Analyze shock environment given the impact forces

Power Backup

Primary Cell Trade Study 1

		Consumer Grade LiFePO4			Defense-Grade Thermal Battery			Deep Space 2 LTC Battery			Traditional LiSOCL2 Battery			Nickel-Hydrogen Battery		
Wants	WT	Info	Value	Score	Info	Value	Score	Info	Value	Score	Info	Value	Score	Info	Value	Score
Volumetric Energy Density	0.25	LiFePO4 batteries have some of the highest energy densities of rechargable cells	0.7	0.175	Thermal batteries allow very high energy density due to rapid chemical reactions	0.95	0.2375	Moderate density, designed for impact survival and low-temperature operation	0.6	0.15	High density, optimized for compact deep-space storage	0.85	0.2125	Low density, limited by gas containment volume	0.1	0.025
			0.75	0.1875		0.98	0.245		0.65	0.1625		0.9	0.225		0.15	0.0375
			0.8	0.2		1	0.25		0.7	0.175		0.95	0.2375		0.2	0.05
Specific Energy (gravimetric density)	0.25	LFP specific energy suffers from the electrode weight and density, although is still high	0.45	0.1125	High specific energy, short-duration power	0.6	0.15	High specific energy	0.9	0.225	Very high specific energy, mass-efficient for long missions	0.85	0.2125	Low specific energy, bulky gas-based system	0.2	0.05
			0.5	0.125		0.65	0.1625		0.95	0.2375		0.9	0.225		0.25	0.0625
			0.55	0.1375		0.7	0.175		1	0.25		0.95	0.2375		0.3	0.075
Availability	0.1	Very available, used in automotive, aerospace, medical, consumer	0.95	0.095	Relatively common from suppliers in defense industry, in active production	0.8	0.08	Custom cell, used only for one mission and related testing. Remanufacture is a possibility	0.1	0.01	Widely available from aerospace and industrial suppliers, used in space, oil/gas, remote sensing, medical	0.85	0.085	Widely considered obsolete, legacy and government programs main clients	0.2	0.02
			0.98	0.098		0.85	0.085		0.15	0.015		0.875	0.0875		0.25	0.025
			1	0.1		0.9	0.09		0.2	0.02		0.9	0.09		0.3	0.03
Impact Tolerance	1	Off-the shelf components can survive 1000-5000g depending on model, but can be ruggedized	0.1	0.1	Depending on design, can handle 50,000-100,000g	0.95	0.95	Specifically designed to tolerate 80,000g+	0.99	0.99	Can possibly survive 20,000g depending on exact design, but unlikely without ruggedization	0.3	0.3	Contains high-pressure storage, can be ruggedized but is catastrophic in event of failure	0.15	0.15
			0.15	0.15		0.975	0.975		0.995	0.995		0.35	0.35		0.2	0.2
			0.2	0.2		1	1		1	1		0.4	0.4		0.25	0.25
Constant and Burst Current Capability	0.75	LFP cells are some of the most tolerant of extreme constant current	0.9	0.675	Can provide high current, but not over long, sustained periods	0.1	0.075	Moderate current capability, designed for stability over longer time periods	0.6	0.45	Ideal for low power draw over long periods, burst power for heater/TX/RX may be an issue	0.4	0.3	Excellent stability under low/moderate load, can tolerate burst power	0.85	0.6375
			0.95	0.7125		0.15	0.1125		0.65	0.4875		0.45	0.3375		0.9	0.675
			1	0.75		0.2	0.15		0.7	0.525		0.5	0.375		0.95	0.7125
Safety Risk	0.5	Thermal runaway is almost impossible, low/moderate risk of hazardous electrolye contamination if breached	0.8	0.4	Very stable; non-reactive until triggered. Generates high heat levels if accidentally triggered	0.6	0.3	Extremely stable under normal operation, small risk of thermal runaway if punctured, moderate chemical hazard	0.5	0.25	Highly corrosive and unstable if containment is breached, very small risk of thermal runaway, increased local hotspots	0.4	0.2	High pressure H2 gas can cause catastrophic unplanned disassembly in event of breach	0	0
			0.85	0.425		0.65	0.325		0.6	0.3		0.5	0.25		0.025	0.0125
			0.9	0.45		0.7	0.35		0.7	0.35		0.6	0.3		0.05	0.025

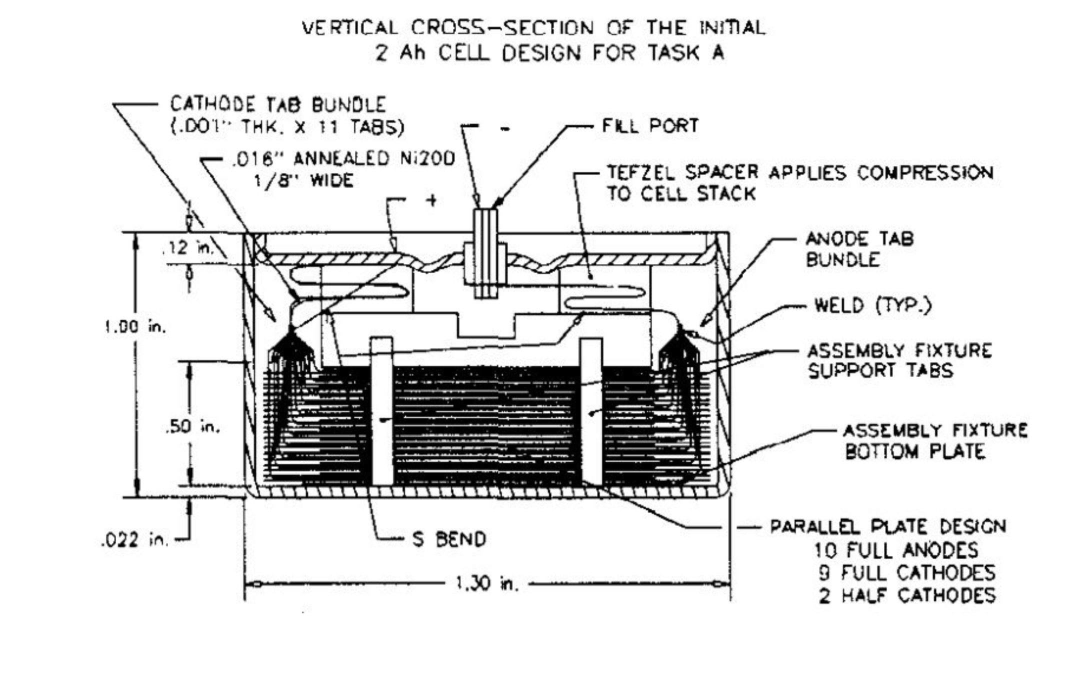
Primary Cell Trade Study 2

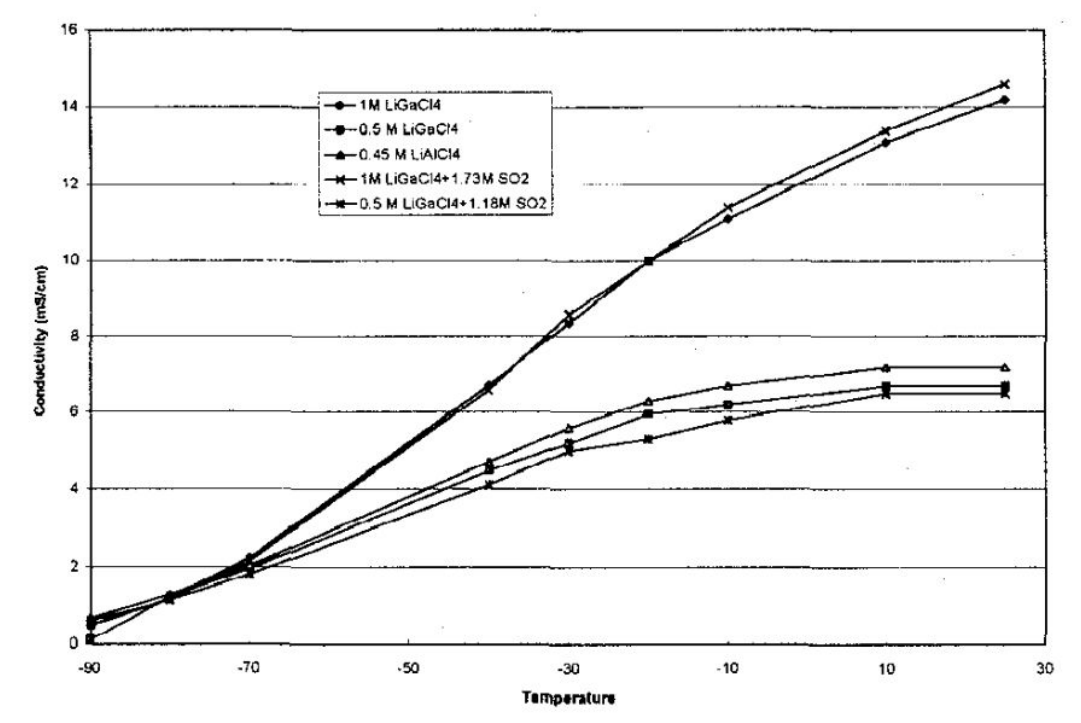
		Consumer Grade LiFePO4			Defense-Grade Thermal Battery			Deep Space 2 LTC Battery			Traditional LiSOCL2 Battery			Nickel-Hydrogen Battery		
Long-term Stability / Self Discharge Rate (10 years)	0.9	Potentially 90% charge loss, but could be kept 'topped off' by orbiter during journey	0.1	0.09	Ideal for long storage, inert with no capacity loss until activated	0.95	0.855	Ultra-low self-discharge, designed to survive multi-year deep-space missions.	0.9	0.81	Excellent long-term storage, proven in space, depending on design less specialized than DS2 LTC	0.85	0.765	Estimated 60% loss over 10 years, would require orbiter battery tender	0.2	0.18
			0.15	0.135		0.975	0.8775		0.95	0.855		0.875	0.7875		0.25	0.225
			0.2	0.18		1	0.9		1	0.9		0.9	0.81		0.3	0.27
Nominal Voltage Stability	0.9	Large initial drop from maximum voltage, moderate 'knee' on discharge curve with sharp drop <20%	0.3	0.27	Moderately stable initial voltage, rapid drop-off as heat dissipates	0.2	0.18	Moderate initial drop, almost constant nominal voltage until <5% capacity		0	Very stable nominal voltage throughout discharge range, with a predictable dropoff <5%	0.75	0.675	Voltage highly dependent on load, stable voltage with stable load	0.15	0.135
			0.35	0.315		0.25	0.225			0		0.775	0.6975		0.2	0.18
			0.4	0.36		0.3	0.27			0		0.8	0.72		0.25	0.225
Scalability / Configurability	0.75	Highly configurable due to wide availability in multiple form factors	0.8	0.6	Generally custom sized, not easily scaled or reconfigured	0.2	0.15	Specicfically designed to be stable, ideally in multiple groups of 4 cells	0.9	0.675	Highly configurable and scalable, available in common standards and custom sizes	0.9	0.675	Configuration highly constained by pressure containment systems, but is configurable	0.35	0.2625
			0.9	0.675		0.25	0.1875		0.925	0.69375		0.95	0.7125		0.4	0.3
			1	0.75		0.3	0.225		0.95	0.7125		1	0.75		0.45	0.3375
Total Score		Minimum		2.5175			2.9775			3.56			3.425			1.46
		Nominal		2.823			3.195			3.74625			3.6725			1.7175
		Maximum		3.1275			3.41			3.9325			3.92			1.975

FINAL DECISION:
Deep Space 2 LTC Battery

Primary Cell Trade Study Overview

- Comparison between consumer, defense, and custom-designed components
- Thermal batteries provide high power, but with drawbacks
  - Capacity
  - Heat Generation
- Traditional LTC and consumer-grade LiPo cannot handle impact conditions
- Solution: Custom designed cells from Deep Space 2 Probes
  - Tolerant of 80,000g impact
  - Sufficient capacity to power scientific instruments

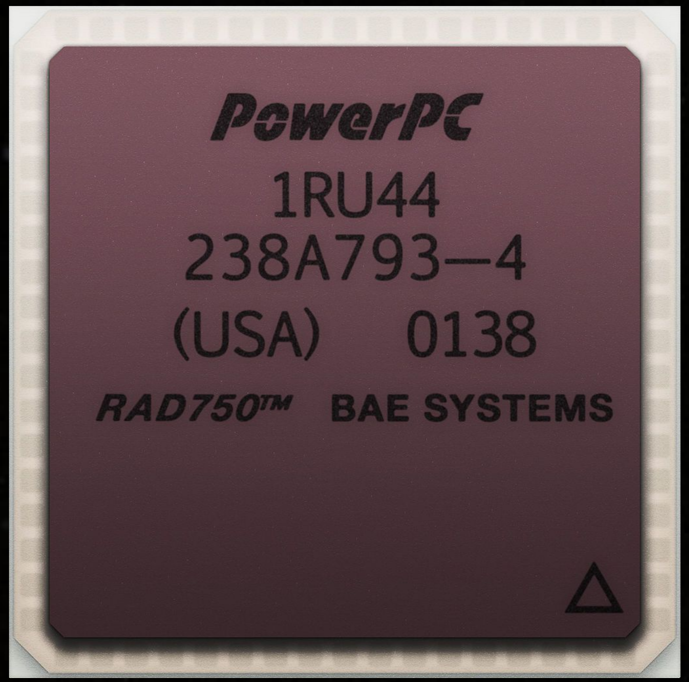




CDH Backup

C&DH

- Microcontroller selection: BAE Systems RAD750
  - Radiation Hardened version of PowerPC750
  - Robust, but expensive



- If a lower, 30krad max dose can be justified:
  - Microchip ATmegaS128
  - 8-bit microcontroller, rad hardened version of µC line commonly used in Arduino

- Total data storage
  - 50GB

TT&C Backup

TT&C Worst Case Link

Item	Symbol	Units	Value	Source	Explanation
Frequency	*f*	GHz	2	Input Parameter	Refer to Frequency Selection table in Communication_Systems_Sep_25-27 lecture
Transmitter Power (DC)	*P*	W	5	Input Parameter	Assume antenna power = 25% of total bus power
Transmitter Power Amplifier Efficiency	*hp*	-	0.6	Input Parameter	Assume TWTA
Transmitter Power (RF)	*P*	W	5	R*hp	
Transmitter Power (RF)	*P*	dbW	6.99	10*log(P)	
Transmitter Line Loss	*Ll*	dB	0.2	Input Parameter	Assume based on Table 16-13 from New SMAD
Transmit Antenna Beamwidth	*θt*	deg	95.45454545	Input Parameter	New equation provided in Slack ; theta = 21/(f/c)*D
Transmit Antenna Efficiency	*ht*	-	0.7	Input Parameter	
Peak Transmit Antenna Gain	*Gpt*	dBi	5.70	Eq. 16-10 from New SMAD	
Transmit Antenna Diameter	*Dt*	m	0.11	Input Parameter	
Transmit Antenna Pointing Error	*et*	deg	10	Input Parameter	

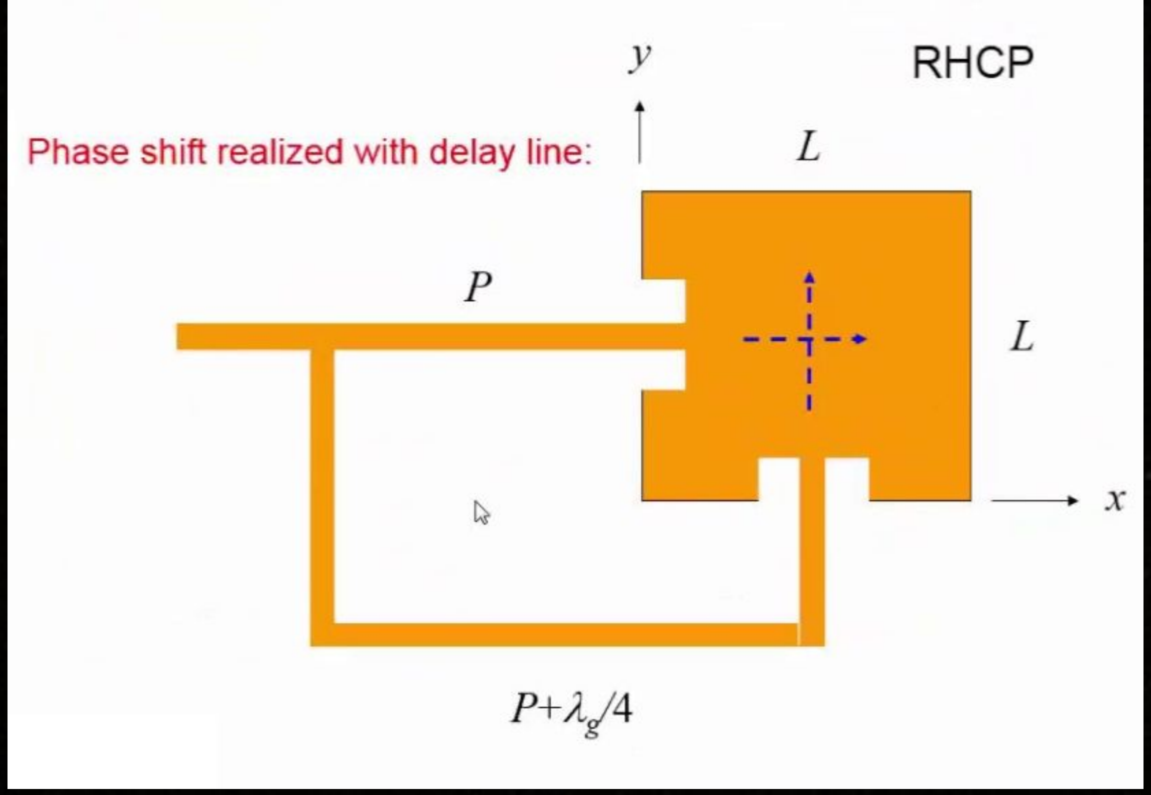
CLASP

Item	Symbol	Units	Value	Source	Explanation
Frequency	*f*	GHz	2	Input Parameter	Refer to Frequency Selection table in Communication_Systems_Sep_25-27 lecture
Transmitter Power (DC)	*P*	W	5	Input Parameter	Assume antenna power = 25% of total bus power
Transmitter Power Amplifier Efficiency	*hp*	-	0.6	Input Parameter	Assume TWTA
Transmitter Power (RF)	*P*	W	5	R*h*p*	
Transmitter Power (RF)	*P*	dbW	6.99	10*log(P)	
Transmitter Line Loss	*Ll*	dB	0.2	Input Parameter	Assume based on Table 16-13 from New SMAD
Transmit Antenna Beamwidth	*θt*	deg	95.45454545	Input Parameter	New equation provided in Slack ; theta = 21/(f/c)*D
Transmit Antenna Efficiency	*ht*	-	0.7	Input Parameter	
Peak Transmit Antenna Gain	*Gpt*	dBi	5.70	Eq. 16-10 from New SMAD	
Transmit Antenna Diameter	*Dt*	m	0.11	Input Parameter	
Transmit Antenna Pointing Error	*et*	deg	5	Input Parameter	
Transmit Antenna Pointing Loss	*Lpt*	dB	0.033	Communication_Systems_Sep_25-27 lecture (slide 46)	
Transmit Antenna Gain (net)	*Gt*	dBi	5.67	Gpt + Lpt (Sample_Link_Budget)	Gain after considering pointing loss
Equiv. Isotropic Radiated Power	*EIRP*	dBW	12.66	Equation 16-20 from New SMAD	

TT&C

- Antenna Design: Patch w/ integrated polarization
  - No moving/deployable parts necessary
  - 6dBi Gain

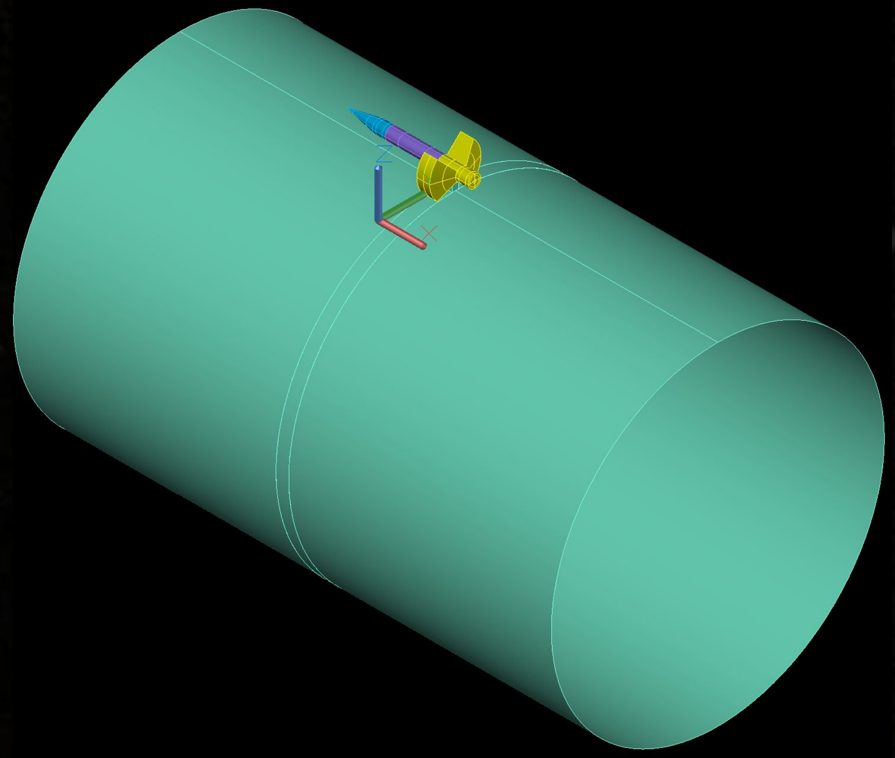
- Optimal Frequency: 2GHz (low-S-band)
  - 15cm wavelength takes advantage of maximal exposed rear-facing surface area
  - Avoids degradation due to water molecule resonance by staying below 2.45GHz
- Link budget allows for ~133dBm received power on orbiter, enough for 2.14mbps data rate

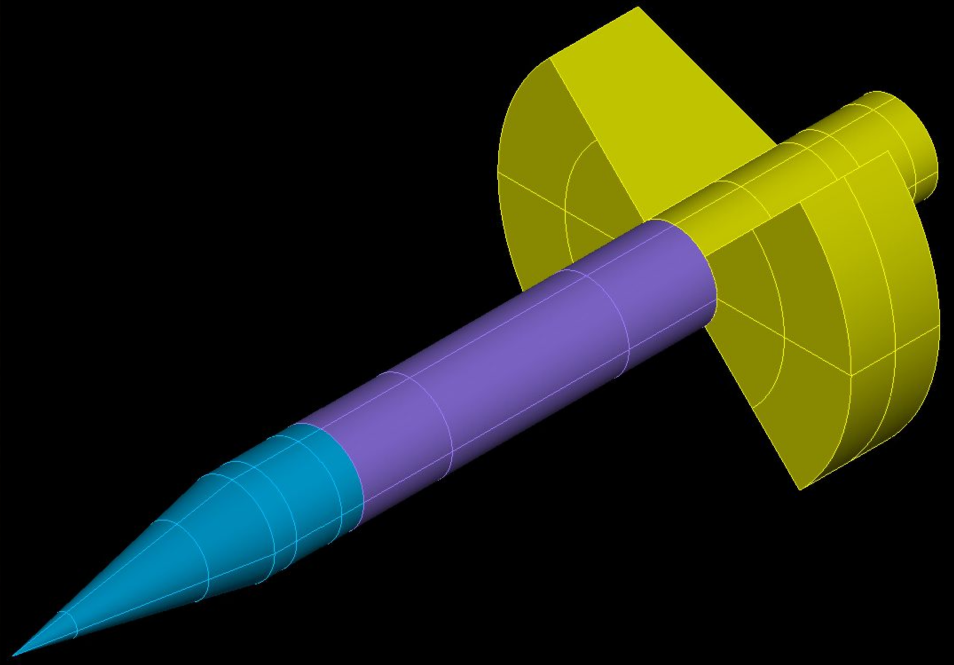


Thermal Backup

70-Node Thermal Analysis (1/2)

- Investigated multiple cases to determine:
  - A possible and realistic thermal control system
    - Passive: Insulation, coatings
    - Active: heaters
  - Survival heater power when attached to orbiter
    - Associated with customer need of staying below 2W of power draw during transit
  - Heat transfer to/from orbiter
- Updated thermal model reflect penetrator mission concept
  - 70 nodes, 103 objects
  - Structural panels
  - Battery component
- Following cases rans:
  - Cold
    - Cold Uranian orbit with and without the orbiter
  - Hot
    - Hot Uranian orbit with and without the orbiter
    - Jovian grav. assist flyby





Environment	Solar (W/m²)	Albedo	IR Planetshine (W/m²)
Uranus Cold	3.7	0.9	0.50
Uranus Hot	3.7	0.9	0.76
Jupiter Hot	50.1	0.343	14.1

70-Node Thermal Analysis (2/2)

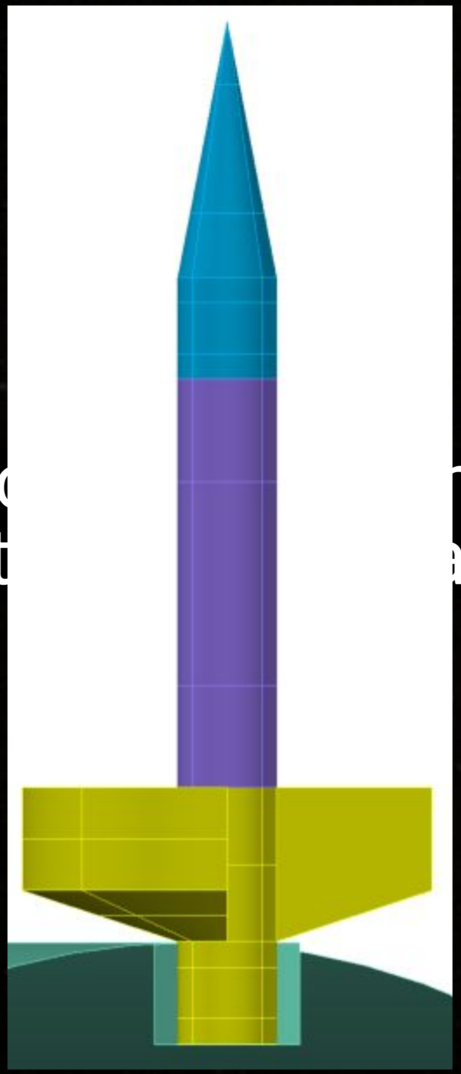
- When attached to the orbiter, survival heaters may not be required
  - Minimum orbiter temperature that allows for no heater power in -38.9°C
- Accounting for environmental heating and conduction paths in model, battery heater power required drops <1 W
  - Excellent for overall lifetime
- Battery survival heater size will be ~1W (0.64*1.5)

Case	Min. Battery Temperature (°C)	Max. Battery Temperature (°C)	Battery Heater Power (W)
Cold Uranian Orbit, w/ Orbiter (-20°C)	-20.2	-20.16	0
Cold Uranian Orbit, w/o Orbiter	-39.0	-39.0	0.64
Hot Uranian Orbit, w/ Orbiter (-20°C)	-20.2	-20.14	0
Hot Uranian Orbit, w/o Orbiter	-39.0	-39.0	0.64
Jovian Grav. Assist Flyby, Orbiter (25°C)	24.7	24.9	0

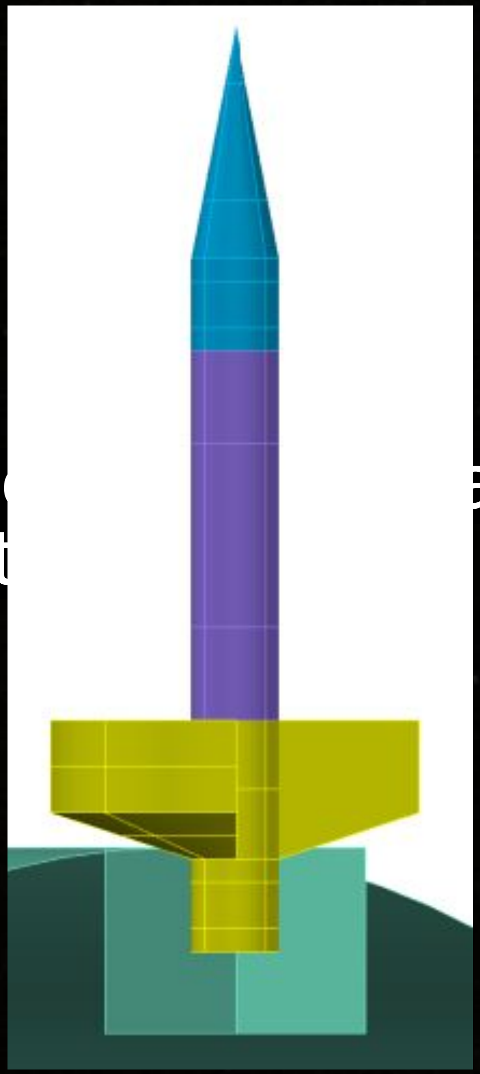
CLASP

Mounting Comparison

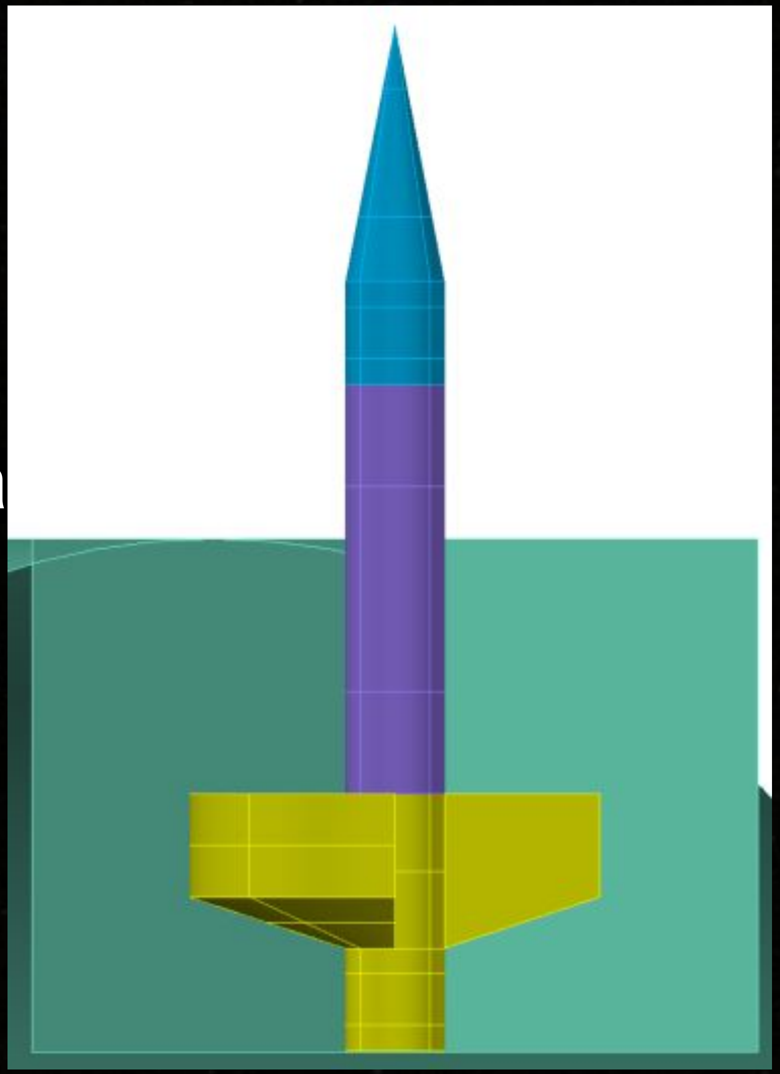
- To obtain data on the impact to heat to/from the c
  study was conducted to compare possible mount
- 5 Models
  - Base orbiter
  - 10cm³ inset
  - 20cm³ inset
  - 50cm³ inset
  - Side Mount
- Orbiter modeled as a 1.3 m radius, 4.2 m long cylinder
  - Set to a boundary temperature
  - Emissivity = 0.035 (e of Al MLI)
- Penetrator based on rough estimate
  - Emissivity = 0.035 (e of Al MLI)
  - Has representative battery object
  - Has heater on battery object
  - No thermal isolation of the batteries
  - Assumed max length of 1 m



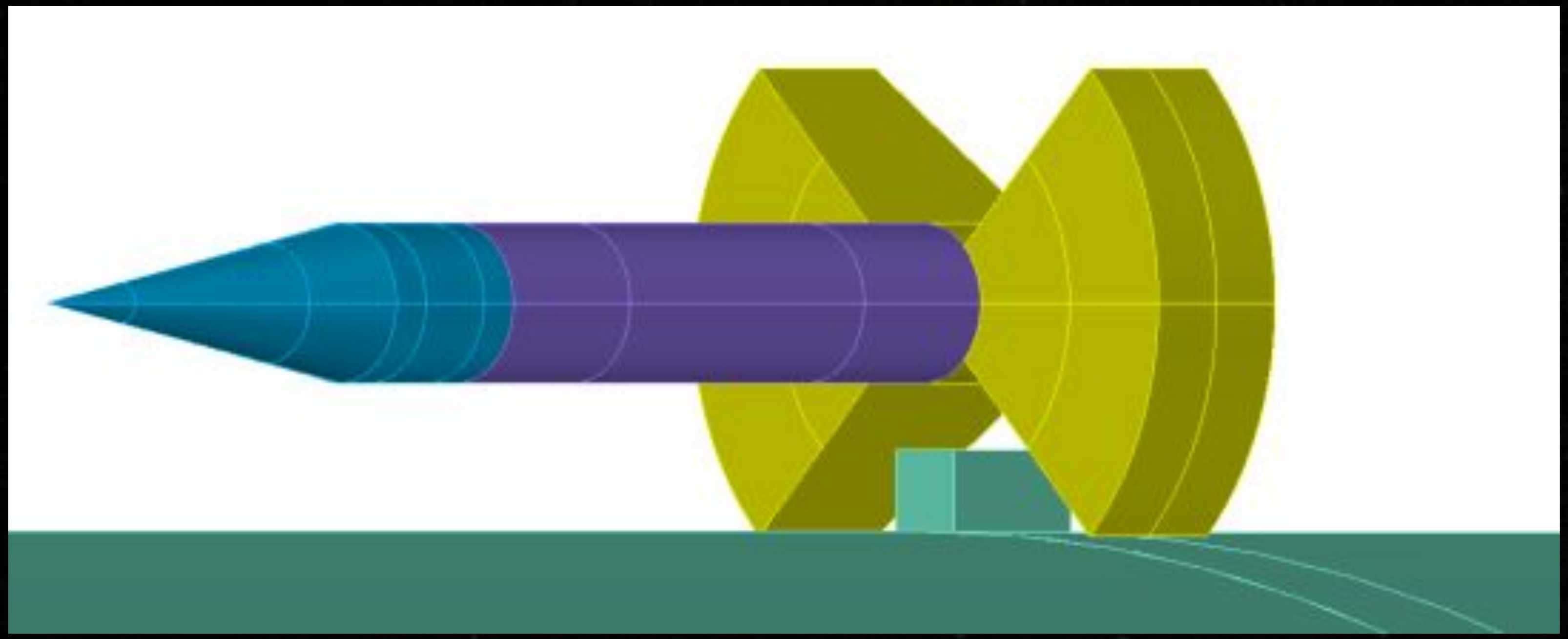
10 cm³



20 cm³



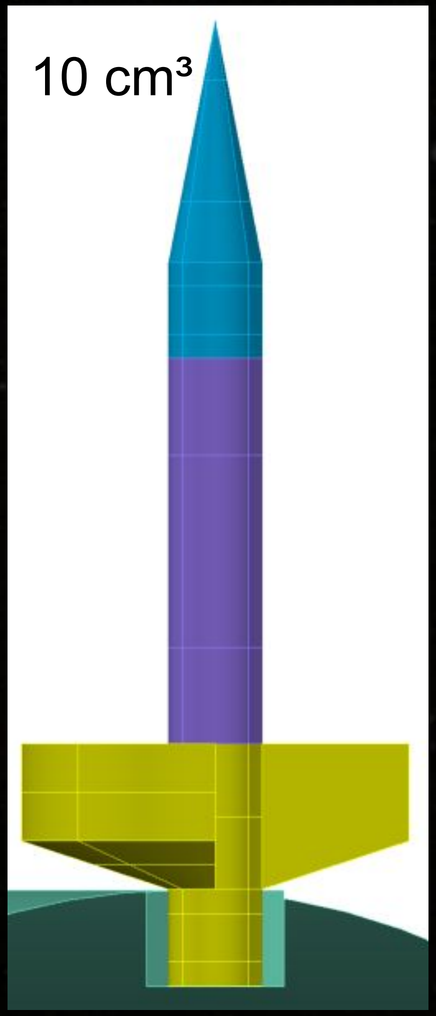
50 cm³

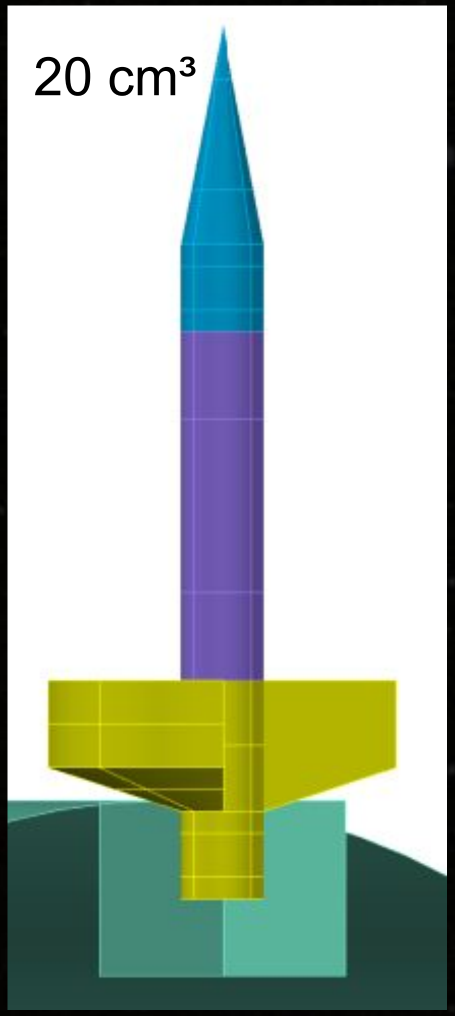


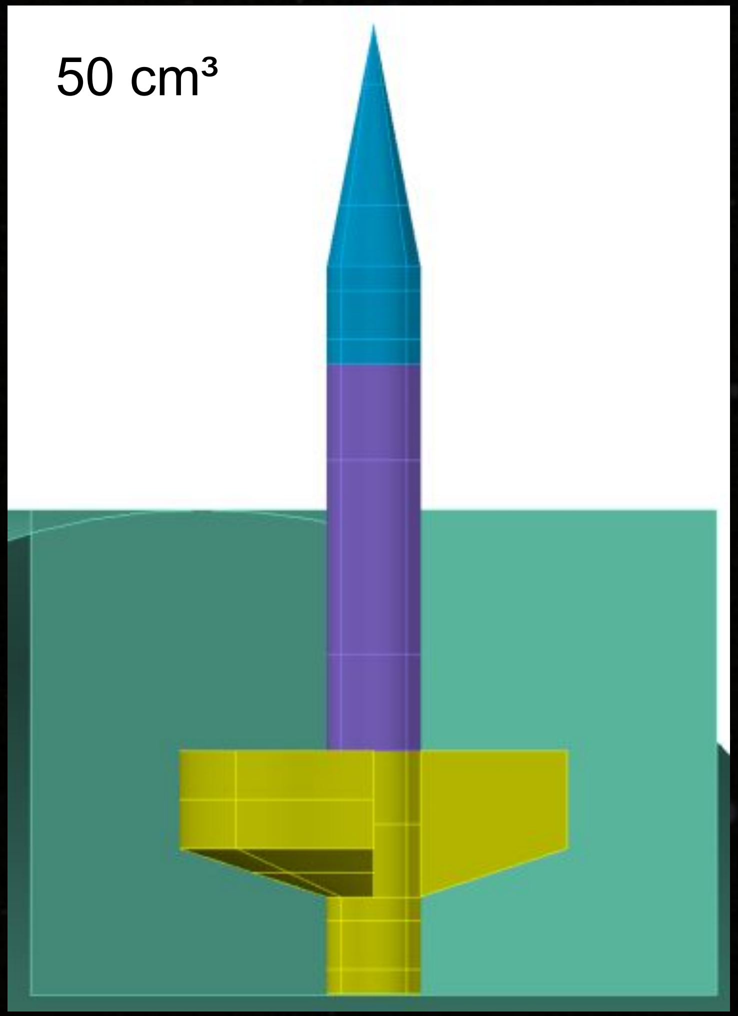
Side Mount

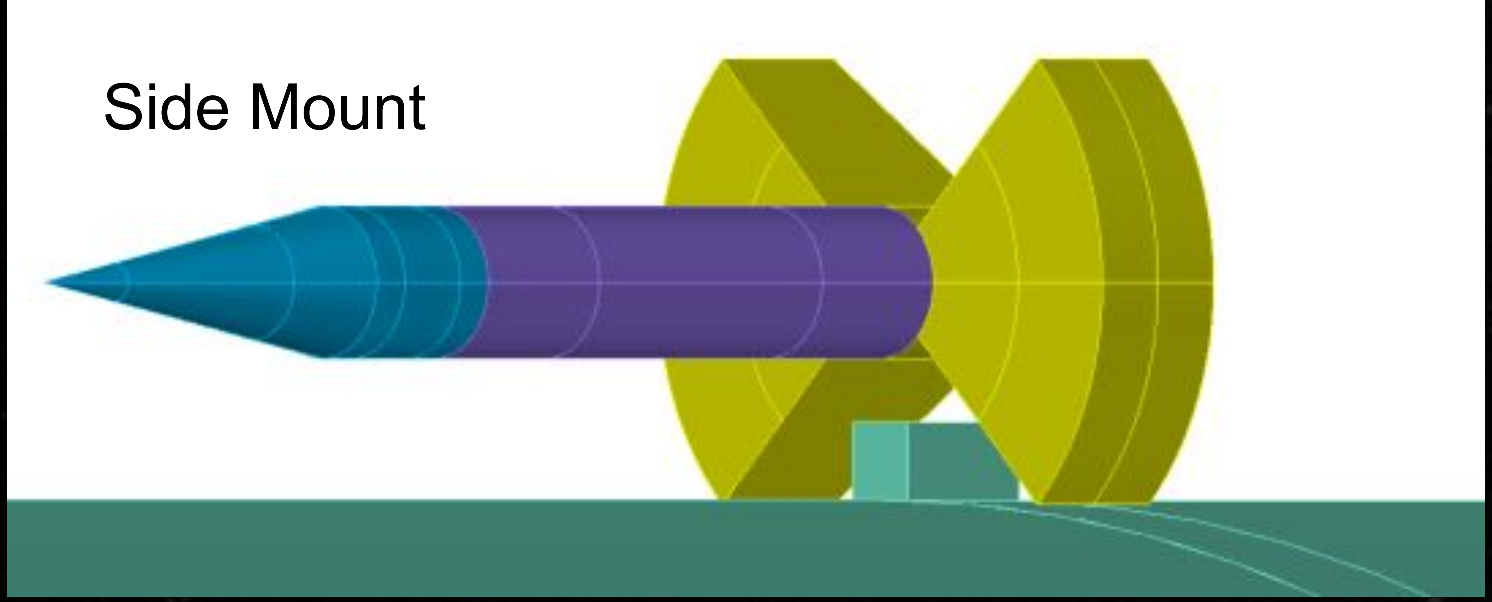
Mounting Comparison

- 4 different mounting options were selected
- Trade study performed by looking at its different impacts on the main orbiter and feasibility
- The results of a thermal mode can be seen below
- The side mounting has the least impact on the orbiters and is therefore chosen as the mounting configuration









Output	Battery Heater Steady State Power (W)			dQ Orbiter Out, w/ Penetrator (W)			dQ Orbiter Out, w/o Penetrator (W)		
Spacecraft Ext Temperature (°C)	-40	-20	0	-40	-20	0	-40	-20	0
Base	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00
Inset Mount 10cm^3	3.55	0.00	0.00	-2.90	0.90	1.22	0.23	0.33	0.44
Inset Mount 20cm^3	3.55	0.00	0.00	-2.42	1.57	2.12	0.94	1.30	1.77
Inset Mount 50cm^3	3.54	0.00	0.00	1.43	6.89	9.35	5.88	8.17	11.08
Side Mount	3.55	0.00	0.00	-3.01	0.74	1.01	0.11	0.16	0.21

Mounting Comparison Results

- Having an inset mounting slightly helps the required internal heat to warm the battery when the external spacecraft temperature is <-38.9°C
- A noticeable impact on the heat out of the orbiter can be observed on the inset mounting configurations
- To minimize impact on the orbiter, the side mounting configuration is recommended

Output	Battery Heater Steady State Power (W)			dQ Orbiter Out, w/ Penetrator (W)			dQ Orbiter Out, w/o Penetrator (W)		
Spacecraft Ext Temperature (°C)	-40	-20	0	-40	-20	0	-40	-20	0
Base	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00
Inset Mount 10cm^3	3.55	0.00	0.00	-2.90	0.90	1.22	0.23	0.33	0.44
Inset Mount 20cm^3	3.55	0.00	0.00	-2.42	1.57	2.12	0.94	1.30	1.77
Inset Mount 50cm^3	3.54	0.00	0.00	1.43	6.89	9.35	5.88	8.17	11.08
Side Mount	3.55	0.00	0.00	-3.01	0.74	1.01	0.11	0.16	0.21

Surface Embedment Heater Analysis (1/2)

- Calculated a steady state thermal balance to determine heat required to keep batteries within operational limits
- Heat load on battery, Q
- Key conductions
  - G1, Icy surface to penetrator structure
    - Assume a high conduction, 100W/K
    - Can be refined in future based on pressure, surface roughness, etc.
  - G2, Penetrator structure to battery
    - Assume some thermal isolation
      - 10 W/K/m², 1/10th of an assumed good bolted area connection
    - Contact area = $2\pi(0.047m)(0.342m) = 0.101m^2$
    - 1.01 W/K
- Battery temperature
  - -45°C = 228.15 K
- Moon surface temperature
  - 30 K, Worst case from [1]
- Q = (T_batt - T_moon)/(R1+R2) = (T_batt - T_moon)/(1/G1+1/G2) =(228.15 K - 30 K)/(1/100 K/W + 1/1.01 K/W) = **198.1 W**

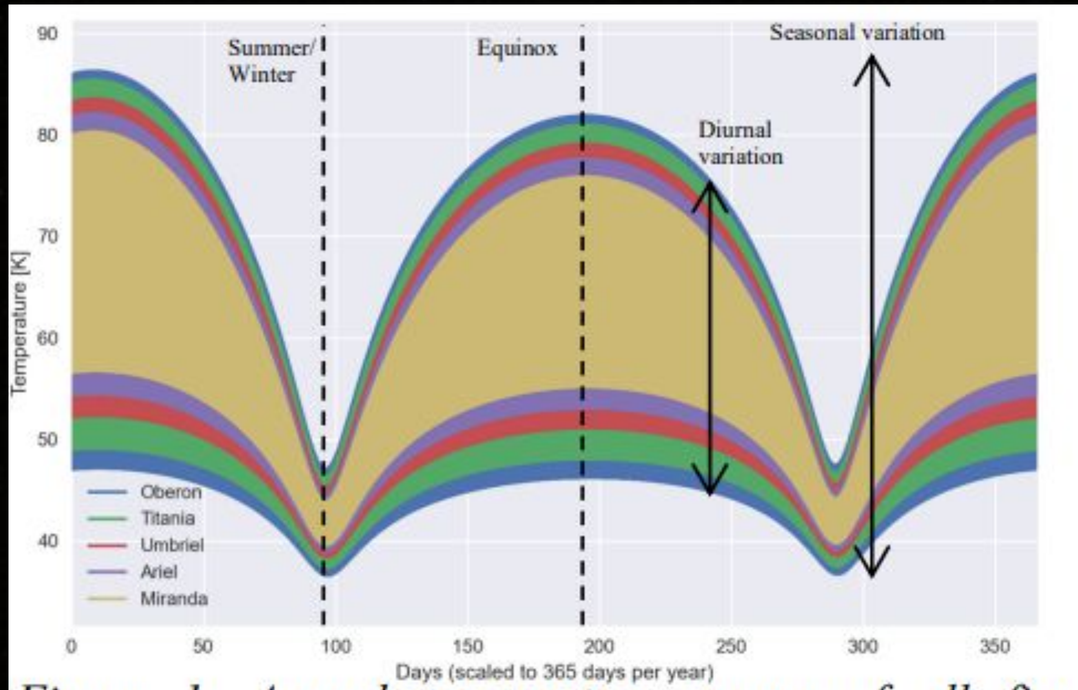
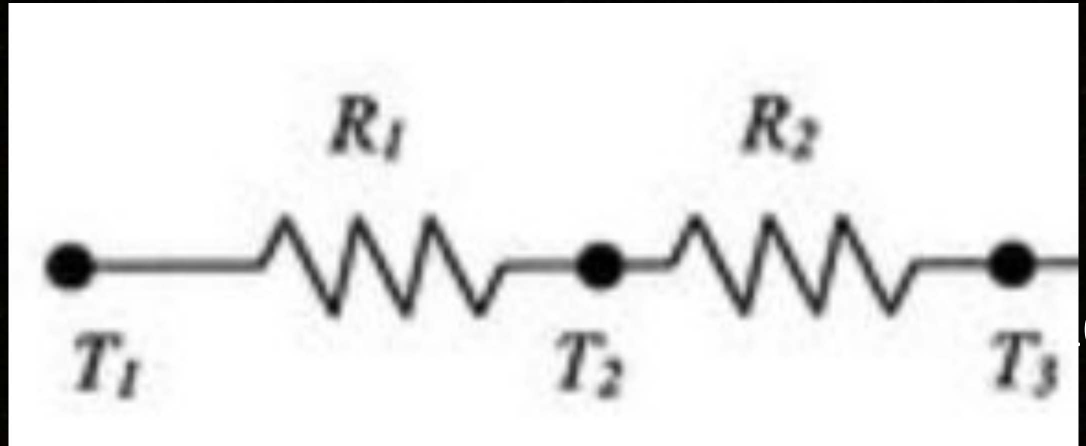


Figure 1. Annual temperature curves of all five satellites. Oberon's diurnal and seasonal variation is greater than that of its fellow satellites due to its longer day.



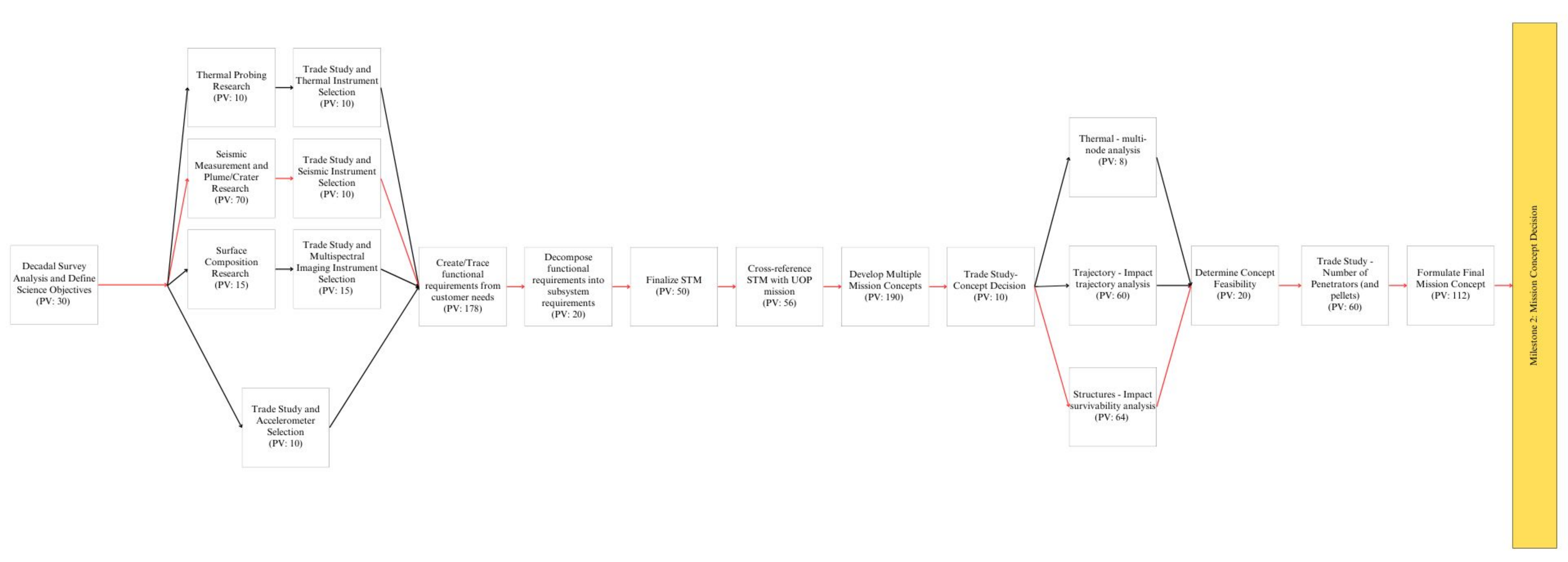
[1] E. C. Cooper. "MODELING SURFACE TEMPERATURES ON THE URANIAN SATELLITES." https://www.hou.usra.edu/meetings/lpsc2022/pdf/2319.pdf

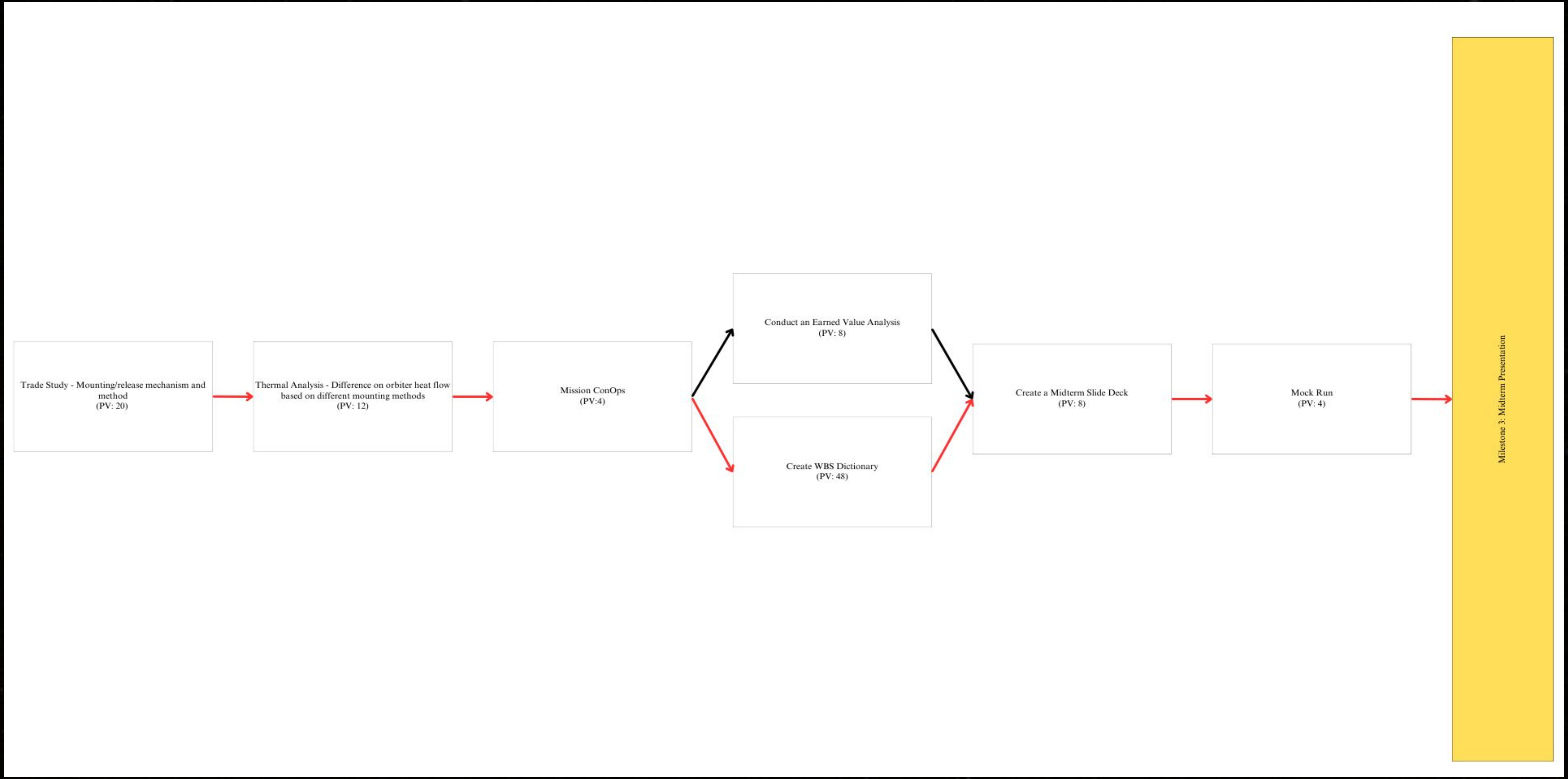
Surface Embedment Heater Analysis (2/2)

- Ran a transient on thermal model to determine how long the battery will remain in operational temperature limits given a steady internal heat load
- Will require significant internal heat to be within the battery operational limits
- Indicator of a short lifetime post-impact to collect, compress, and transmit data

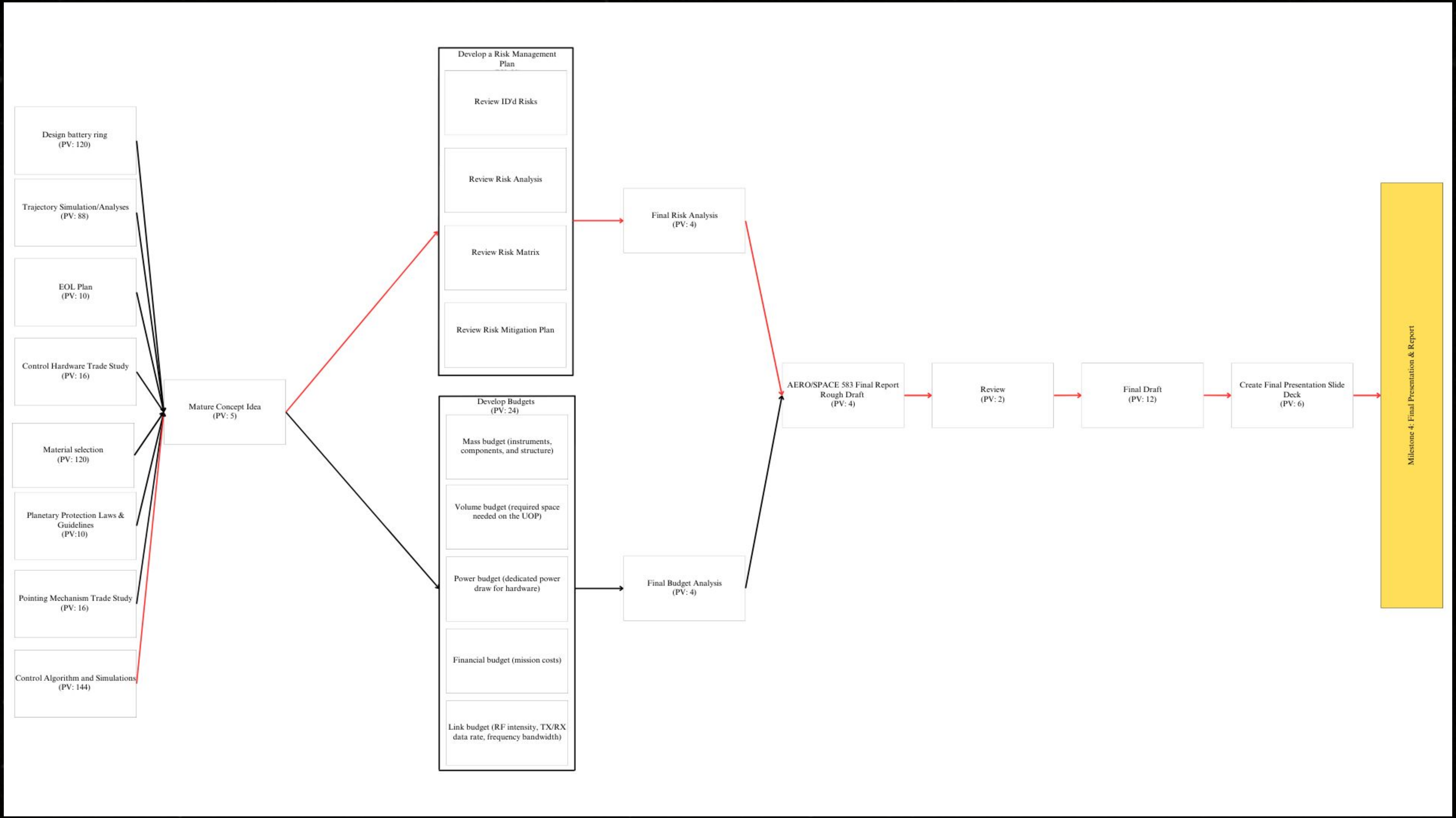
Survival Time	Surface Temp = 70K Internal Heat (W)	Surface Temp = 30K Internal Heat (W)	Notes
1 min	0	0	From initialized temps, survives w/o heater power
10 min	9	32	
30 min	102	135	
1 hour	128	163	
6 hours	147	184	
12 hours	148	185	
1 day	148	185	
1 week	148	185	
1 month	148	185	

Critical Path

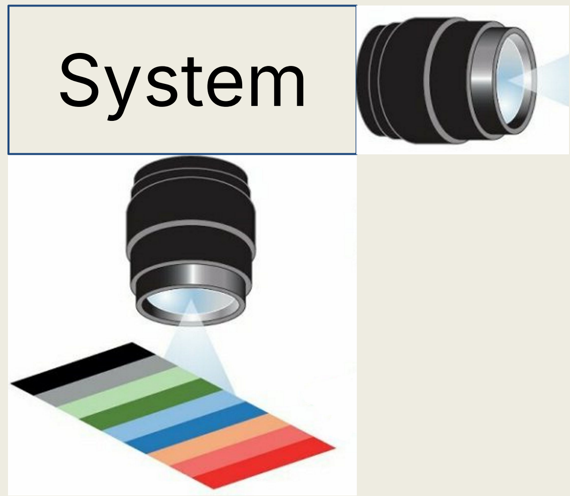




Trade Study - Mounting/release mechanism and method
(PV: 20)
Thermal Analysis - Difference on orbiter heat flow based on different mounting methods
(PV: 12)
Mission ConOps
(PV:4)
Conduct an Earned Value Analysis
(PV: 8)
Create WBS Dictionary
(PV: 48)
Create a Midterm Slide Deck
(PV: 8)
Mock Run
(PV: 4)
Milestone 3: Midterm Presentation


Design battery ring (PV: 120)
Trajectory Simulation/Analyses (PV: 88)
EOL Plan (PV: 10)
Control Hardware Trade Study (PV: 16)
Material selection (PV: 120)
Planetary Protection Laws & Guidelines (PV:10)
Pointing Mechanism Trade Study (PV: 16)
Control Algorithm and Simulations (PV: 144)
Mature Concept Idea (PV: 5)
Develop a Risk Management Plan
Review ID'd Risks
Review Risk Analysis
Review Risk Matrix
Review Risk Mitigation Plan
Develop Budgets (PV: 24)
Mass budget (instruments, components, and structure)
Volume budget (required space needed on the UOP)
Power budget (dedicated power draw for hardware)
Financial budget (mission costs)
Link budget (RF intensity, TX/RX data rate, frequency bandwidth)
Final Risk Analysis (PV: 4)
Final Budget Analysis (PV: 4)
AERO/SPACE 583 Final Report Rough Draft (PV: 4)
Review (PV: 2)
Final Draft (PV: 12)
Create Final Presentation Slide Deck (PV: 6)
Milestone 4: Final Presentation & Report

Multi-Spectral & Side-View Imager

Decadal Survey Recommendation	Science Goals	Scientific Objectives	Measurement	Nominal Instrument	Functional Requirement
Q5.1c How Does Porosity, Ices, Liquids, or Gases Affect the Physical Properties of the Crust? Q12.8a What Can Observations of Material Reveal About Formation of Circumplanetary Systems?	Collect images of surface	Spectral composition and topography of surface	Observe surface during descent: Nadir-facing & azimuth facing	1. Downward facing multi-spectral imager (R, G, B, NIR-1, NIR-2; 10m) 2. Side-view imager (Visible; 10m) 	1. Descent velocity shall allow sufficient time for image capture, processing, and onboard storage. 2. Penetrator shall shield imager from environment and vibrations on descent

Vis/NIR Imaging Spectrometer & WAC (Lucy L'Ralph)

Decadal Survey Recommendation	Science Goals	Scientific Objectives	Measurement	Nominal Instrument	Functional Requirement
Q5.1c How Does the Presence of Porosity, Ices, Liquids, or Gases Affect the Physical (e.g., Mechanical, Thermal, Electromagnetic) Properties of the Crust? Q12.8a What Can Observations of Circumplanetary Material Reveal About the Formation and Evolution of Circumplanetary Systems?	Determine chemical composition of the moon's surface.	Quantify key chemical elements and minerals in the satellite's impact plume.	Vis Spectroscopy (remote sensing) Imaging of impact flash	Vis/NIR Imaging Spectrometer & WAC (Lucy L'Ralph) (Note - This will be on main orbiter)	The penetrator shall maintain line of sight with the orbiter during its impact. Maximize regolith displacement for orbiter to image.
	Measure impact site physical properties on the large moon.	Determine surface hardness of the Uranian moons	Crater size at impact site of penetrators and impactors		The penetrator shall create a crater with radius 3-15 meters for the flagship mission to image
Q4.4b What Materials Ejected from Impact Craters Are Deposited on Planetary Surfaces?	Observe the trajectories of ejecta from ice moon impacts	Observe the impact on the moon's surface Calculate ejecta percentages: surface return, escape, or orbit.	Surface imagery		1. The penetrator shall impact the moon within line of sight of the orbiter 2. The pellet shall impact the target moon only during flybys where the orbiter's altitude is less than 500 km

Uniaxial impact accelerometer

Decadal Survey Recommendation	Science Goals	Scientific Objectives	Measurement	Nominal Instrument	Functional Requirement
Q5.1c How Does the Presence of Porosity, Ices, Liquids, or Gases Affect the Physical (e.g., Mechanical, Thermal, Electromagnetic) Properties of the Crust?	Determine the physical properties of the large moon's surface at the point of impact	Determine the surface hardness of the Uranian moons	Deceleration profile	Uniaxial impact accelerometer	The accelerometer must record data at [TBR] readings/sec to detect the exact moment of impact and the subsequent deceleration profile

CLASP | JPL

MEMS Seismometer

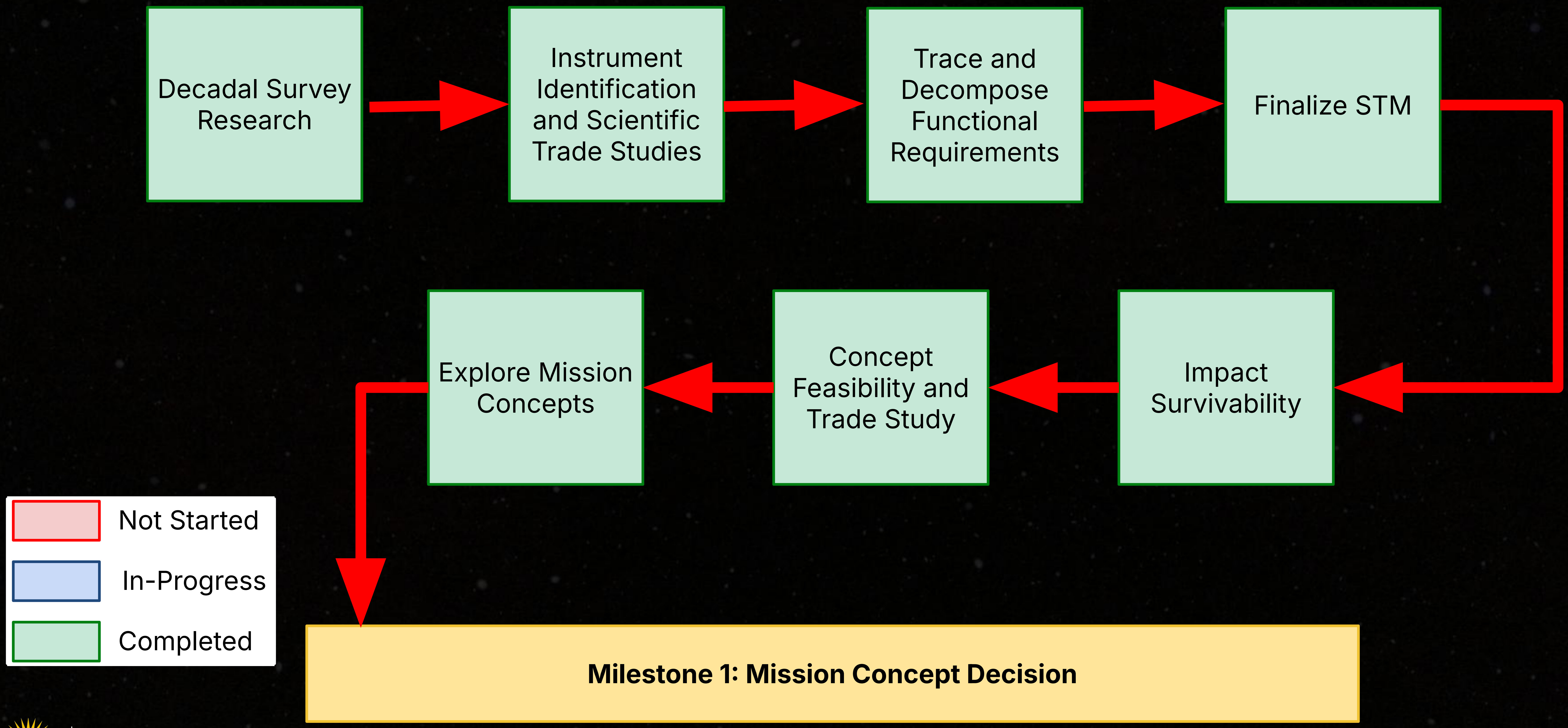
Decadal Survey Recommendation	Science Goals	Scientific Objectives	Measurement	Nominal Instrument	Functional Requirement
Q5.1a How Much Variability in Composition and Internal Structure Is There Within and Between Solid Bodies, and How Did Such Variability Arise and Evolve?	Probe the interior of the Uranian satellites	Determine the interior composition and structure of the Uranian moons Determine the thickness of the ice sheet of Uranian moons	Seismic Noise If staying on the surface (Coda of Body waves, harmonic frequency of Crary wave)	MEMS Seismometer	The penetrator should survive the impact The instrument shall have a high signal to noise ratio

CLASP | JPL

Germanium RTDs

Decadal Survey Recommendation	Science Goals	Scientific Objectives	Measurement	Nominal Instrument	Functional Requirement
Q8.2f How Are Heat and Material Transported Through—and Ultimately Out of—Satellite Interiors? Q5.1a How Much Variability in Composition and Internal Structure Is There Within and Between Solid Bodies, and How Did Such Variability Arise and Evolve?	Determine the thermal properties of the moon's surface	Infer thermal conductivity and heat dissipation rates across the surface of the moon	1. Measure post-impact temperature decay in regolith 2. Compare temperature profiles at different depths (2) within the impactor	Germanium Resistance Temperature Detector	1. RTD shall survive expected impact forces. 2. RTD shall remain operational in low temperatures 3. RTD shall take high-frequency temperature readings post-impact 4. RTD shall provide 1kb of data per hour even with minimal battery life, up to one week. 5. RTD shall delve at least 0.5 meters into the surface of the satellite

Critical Path: Milestone 0-1



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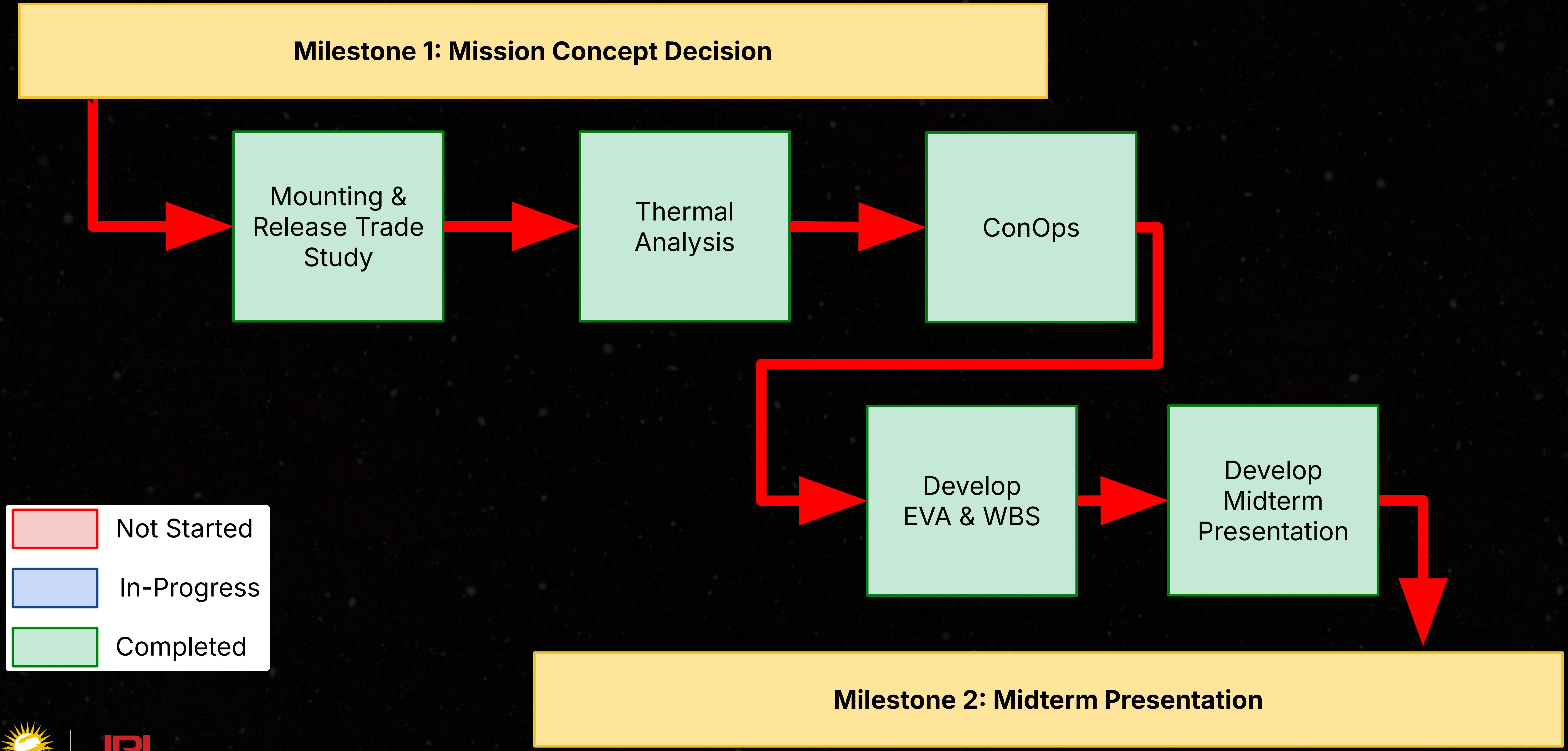
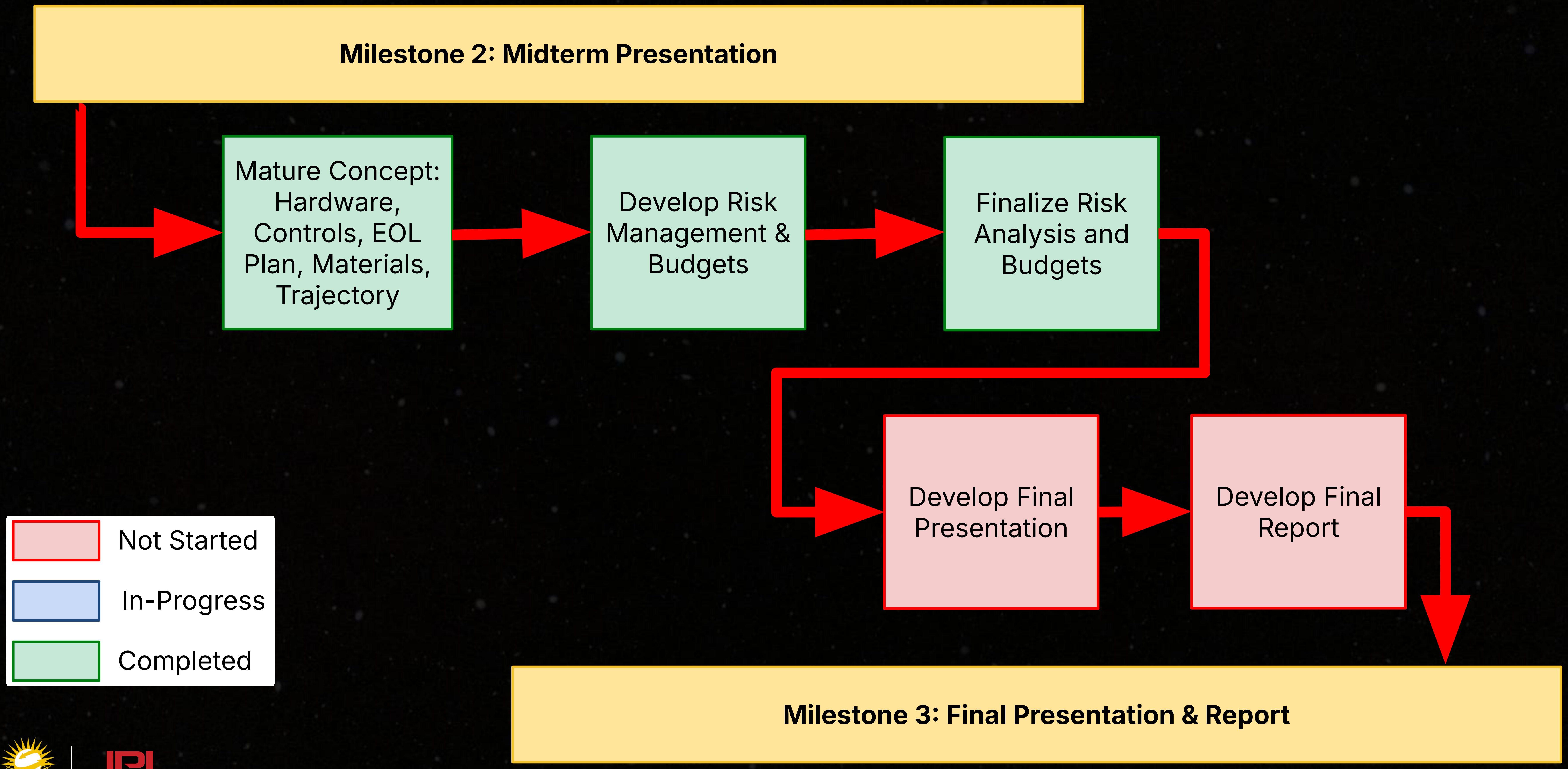
Critical Path: Milestone 1-2



Critical Path: Milestone 2-3



Camera Trade Study

Trade Matrix

PERCI Instrument Trade Study: Cameras

Choices Criteria	DRACO Imager (Baseline)		OSIRIS REX SamCam/TAGCAMS (ECAM M50)		Deep Impact Impactor Targeting Sensor (ITS)		SDL Deep Space Imager		Crystal Space Cubsat Camera	
Must Haves	Info	Y/N	Info	Y/N	Info	Y/N	Info	Y/N	Info	Y/N
Shall have a maximum mass of ~5 kg.	9.55 kg, but this is also one of the primary instruments for DRACO so they were probably able to provide more mass/volume for this	No	4 kg, SAMCAM interfaces with the TAGCAM so lumped the mass together	Yes	10 kg, approximate mass, the HRI/MRI mass is supposed to be 90 kg. and the MRI is much smaller and the same as ITS with no focal wheel	No	1 kg, small cubesat like imagers that are rad tolerant	Yes	50 g, we can stack these but not sure if they are rad tolerant	Yes
Shall have a maximum volume of ~0.02 m^3.	0.03 m^3, rough guess based on the diameter and length	No	0.02 m^3, making an estimate based on the diameter and length of both cams	Yes	0.02 m^3, making an estimate based ont he diameter and length	Yes	0.002 m^3	Yes	0.0001 m^3	Yes
Does not exceed maximum power draw of the secondary payload. (~10W)	Uses 4.95 W power for electronics and 5.2 W for heaters, so barely making it	No	~10 W. total power draw of camera suite is 30.2 W	Yes	30 W, the MRI uses 40W, so I assumed that it would be less	No	2 W	Yes	1 W	Yes
Shall capture and store or transmit imaging data prior to impact		Yes		Yes		Yes		Yes		Yes

DRACO Imager (Baseline) / OSIRIS REX SamCam/TAGCAMS (ECAM M50)

Wants	WT	Info	Value	Score	Info	Value	Score
Survivability (Radiation / Thermal)	10	Deep space tested, good sensitivity and thermal stability	0	0	Deep space tested, and rad tested within the last 10 years	0	0
	10		1	10		1	10
	10		1	10		1	10
Operation in Low Light Conditions	9	Optimized for imaging dark asteroids surfaces	0	0	Large optics? (f/3.5) and adjustable exposure, good low light ability	0	0
	9		1	9		1	9
	9		1	9		1	9
Capabilities (UF: frequency value is the max observed frequency and normalized to min: 400 nm and	9	400-1000 nm, Visible to NIR	0	0	400-800 nm, bandpass, six position filter wheel, visible	0	0
	9		1	9		0.6666666667	6
	9		1	9		1	9
Provide ADCS Support During Transit	8	Used in DART's SMARTNAC guidance system	0	0	The point of TAGCAM is to provide navigation and ADCS for the impactor.	0	0
	8		1	8		1	8
	8		1	8		1	8
Wide FOV	7	(0.29 deg), but high resolution and not optimized for	0	0	horizontal FOV with the 3.85 mm focal length and if MAPCAM is	0	0
	7		0.4	2.8		0.7	4.9
	7		1	7		1	7
High Frame Rate	6	Sample every 5 seconds. Good at prox but not high speed vid	0	0	2.8 fps (200 Mbit/s SpW), looked this up its not high speed but enough for navigation and helpful for ADCS	0	0
	6		0.4	2.4		0.6	3.6
	6		1	6		1	6
Ease of Integration	5	Large, heaviest in this suite, can't just be used as a standalone	0	0	modular, this could be a good thing for us, we can pick and choose the cams we want	0	0
	5		0.1	0.5		0.7	3.5
	5		1	5		1	5
Previous Heritage	4	Most recent deep space impact type mission	0	0	Recent, and successful flight on OSIRIS REX, high TRL	0	0
	4		1	4		1	4
	4		1	4		1	4
EMI/EMC Compatibility	3	Likely rated, unsure, should be okay with SEIS	0	0	Likely rated, unsure, should be okay with SEIS	0	0
	3		0.6	1.8		0.6	1.8
	3		1	3		1	3
Onboard Processing	2	Some info on compression filtering etc, but prob not fully there	0	0	Some onboard processing? Not fully all there	0	0
	2		0.5	1		0.5	1
	2		1	2		1	2
Total Score		Minimum		0	Minimum		0
		Nominal		**48.5**	Nominal		**51.8**
		Maximum		55	Maximum		55
Total Solution Cost		Mimimum:			Mimimum:		
		Nominal:			Nominal:		
		Maximum:			Maximum:		

Deep Impact Impactor Targeting Sensor (ITS) / SDL Deep Space Imager

Wants	WT	Info	Value	Score	Info	Value	Score
Survivability (Radiation / Thermal)	10	Designed for deep space, and survived impact, and rad hardened	0	0	Explicitly states it is rad hardened, designed for LEO, GEO, and long term orbits	0	0
	10		1	10		1	10
	10		1	10		1	10
Operation in Low Light Conditions	9	Was used for navigating and imaging in a dim low light environment	0	0	Offers binning and integration time, which is good for low light	0	0
	9		0.9	8.1		1	9
	9		1	9		1	9
Capabilities (UF: frequency value is the max observed frequency and normalized to min: 400 nm and	9	400-700 nm, visible	0	0	Optional RGB Bayer or hyperspectral filters add to DISC's wide range of	0	0
	9		0.5	4.5		1	9
	9		1	9		1	9
Provide ADCS Support During Transit	8	Was used for ADCS when in transit to the comet	0	0	Can perform centroiding and tracking but nothing about navigation	0	0
	8		1	8		0.5	4
	8		1	8		1	8
Wide FOV	7	and enough for guidance so probably good enough?	0	0	but it is a pretty compact form factor and less than that of the others so	0	0
	7		0.7	4.9		0.3	2.1
	7		1	7		1	7
High Frame Rate	6	Not focused on high frame rate, more on navigation imaging	0	0	Says it is adjustable and not fully defined, but the system appears to be very flexible	0	0
	6		0.3	1.8		0.5	3
	6		1	6		1	6
Ease of Integration	5	enough to remove the filter wheel, this could be useful for us	0	0	lightweight and modular, looks like it can be used for cubesats and	0	0
	5		0.9	4.5		0.9	4.5
	5		1	5		1	5
Previous Heritage	4	mission and provided science relevant data	0	0	credibility, no deep space flight related to this instrument	0	0
	4		1	4		0.5	2
	4		1	4		1	4
EMI/EMC Compatibility	3	instruments like HRI so assuming its probably good	0	0	Designed with rad tolerance so most likely compliant but	0	0
	3		0.6	1.8		0.6	1.8
	3		1	3		1	3
Onboard Processing	2	like it went directly to the primary spacecraft	0	0	and tracking, seems like it explicitly has more onboard	0	0
	2		0.4	0.8		1	2
	2		1	2		1	2
Total Score		Minimum		0	Minimum		0
		Nominal		**48.4**	Nominal		**47.4**
		Maximum		55	Maximum		55
Total Solution Cost		Mimimum:			Mimimum:		
		Nominal:			Nominal:		
		Maximum:			Maximum:		

Crystal Space Cubsat Camera

Wants	WT	Info	Value	Score
Survivability (Radiation / Thermal)	10	Rad hardened but not proven in deep space, good for LEO	0	0
	10		0.6	6
	10		1	10
Operation in Low Light Conditions	9	No mention of control or binning, or a sensitiviy to low light readings	0	0
	9		0.4	3.6
	9		1	9
Capabilities (UF: frequency value is the max observed frequency and normalized to min: 400 nm and	9	400-700 nm, probably basic visible	0	0
	9		0.5	4.5
	9		1	9
Provide ADCS Support During Transit	8	No onboard nav features that use this camera, seems like its mainly to take pictures and not for tracking	0	0
	8		0.3	2.4
	8		1	8
Wide FOV	7	degree field of view, less than the 80 deg that OCAM offered	0	0
	7		0.5	3.5
	7		1	7
High Frame Rate	6	Captures data at 70 deg/rotation, seems to be optimized for rapid capture	0	0
	6		1	6
	6		1	6
Ease of Integration	5	small, low power, seems to adapt to multiple different	0	0
	5		1	5
	5		1	5
Previous Heritage	4	Claims heritage but only in LEO, not for deep space	0	0
	4		0.4	1.6
	4		1	4
EMI/EMC Compatibility	3	Low power helps, not sure if its certified	0	0
	3		0.5	1.5
	3		1	3
Onboard Processing	2	No onboard processing, will require reliance on external hardware	0	0
	2		0.3	0.6
	2		1	2
Total Score		Minimum		0
		Nominal		**34.7**
		Maximum		55
Total Solution Cost		Mimimum:		
		Nominal:		
		Maximum:		

Accelerometer Trade Study

PERCI Instrument Trade Study: Accelerometer

Choices	HBK TYPE 8309		CRL Model 383		CRL Model 876		PCB Piezotronics Model 350B41		PCB Piezotronics Model 250B42	
Links	TYPE 8309 Piezoelectric Charge Shock Accelerometer, Integral Side Cable		Columbia Research Laboratories - Model 383		Columbia Research Laboratories - Model 876		Model 350B41		Model 350B42	
Must Haves	Info	Y/N	Info	Y/N	Info	Y/N	Info	Y/N	Info	Y/N
Commercial off the shelf (COTS)	COTS	Yes	COTS This sensor is built by a research laboratory - very low inventory	No	COTS This sensor is built by a research laboratory - very low inventory	No	COTS	Yes	COTS	Yes
Piezoelectric (Charge Accelerometer)	Piezoelectric	Yes	Piezoelectric	Yes	Piezoelectric	Yes	Piezoelectric	Yes	Piezoelectric	Yes
A13 High amplitude range / shock tolerance (>13000 g's)	3 grams	Yes	0.28 Oz = ~7.37 grams	Yes	1.2 Oz = ~34.02 g	Yes	27 g	Yes	27 g	Yes

Wants	Wt	Info	Value	Score	Info	Value	Score	Info	Value	Score	Info	Value	Score	Info	Value	Score
Low dynamic noise range	6	23 mg	1	6	N/A	0	0	N/A	0	0	N/A	0	0	N/A	0	0
High amplitude range / shock tolerance (>13000 g's)	10	Highest operating shock 15000 g's	1	10	Shock limit 20000 g's	0.7	7	Shock limit 10000 g's (1/2 sine)	0.5	5	1000000 g peak	1	10	50000 g peak	0.8	8
High sensivity - How many output volts per unit of acceleration (~10 mV/g)	7	0.004 pC/g Does not give its capacitance, so I am not sure what its sensitivity in voltage is	0	0	0.5 pC/g = 1.5 mV/g	0.85	5.95	@-420 deg F to -295 deg F 25 pC/g with 5% variability = 1.47 mV/g	0.853	5.971	0.05 mV/g	0.995	6.965	0.1 mV/g	0.99	6.93
High frequency range - within frequency range of SRS (~3 KHz) NOTE: Important to determine frequency response before final selection	7	1-54000 Hz If the instrument can measure the maximum frequency expected, it passes	1	7	2-15000 Hz If the instrument can measure the maximum frequency expected, it passes	1	7	2 - 4000 Hz If the instrument can measure the maximum frequency expected, it passes	0.8	5.6	4 - 10000 Hz If the instrument can measure the maximum frequency expected, it passes	1	7	4 - 10000 Hz If the instrument can measure the maximum frequency expected, it passes	1	7
High usable bandwidth Hard to determine without frequency response	8	N/A		0	N/A		0	N/A		0	N/A		0	N/A		0
Amplitude non-linearity	7	N/A	0	0	1% / 2000 g	0.99	6.93	1% / 2000 g	0.99	6.93	2.5% / 10000 g	0.975	6.825	2.5% / 10000 g	0.975	6.825
Large operating temperature range Ideal: -30 - > 150 C	10	-74 - 180 C Score = (range below op temp - range above max temp spike)/100	1	10	-54 - 175 C	1	10	-267 - 149 C	1	10	-23 - 66 C Operating	0.9	9	-23 - 66 C operating	0.9	9
Vacuum safe Not sure how to look for this information on data sheets	7															
Previous heritage	8															
		Nominal		33	Nominal		36.88	Nominal		33.501	Nominal		39.79	Nominal		37.755

Total Solution Cost	Mimimum:		Mimimum:		Mimimum:		Mimimum:		Mimimum:	
	Nominal:		Nominal:		Nominal:		Nominal:		Nominal:	
	Maximum:		Maximum:		Maximum:		Maximum:		Maximum:	

Seismometer Trade Study

PERCI Instrument Trade Study: Seismometer

	Trillium Compact Horizon		Artius		Episensor		Trillium Compact		STRYDE Node Range+		MEMS Seismometer		GS-1 Seismometer		GeoSIG arolla	
	https://nanometrics.ca/hubfs/Downloads/Data%20Sheets/trillium_compact_horizon.pdf		https://www.guralp.com/products/artius		https://kinemetrics.com/wp-content/uploads/2017/04/datasheet-episensor-es-t-f		https://nanometrics.ca/hubfs/Downloads/Data%20Sheets/trillium_compact.pdf		https://dqifccr9a141x.cloudfront.net/specsheet/The-STRYDE-Node_Range-Spe		https://microdevices.jpl.nasa.gov/capabilities/nano-and-micro-systems/		https://www.geospace.com/products/sensors/gs-1-seismometer/?utm_source=cha		https://www.geospace.com/products/sensors/gs-1-seismometer/?utm_so	
es	Info	Y/N	Info	Y/N	Info	Y/N	Info	Y/N	Info	Y/N	Info	Y/N	Info	Y/N	Info	Y/N
ial off the shelf (COTS)	COTS	Yes	COTS	Yes	COTS	Yes	COTS	Yes	COTS	Yes	In dev at JPL	No	COTS	Yes	COTS	Yes
	1.1 kg	Yes	1.4 kg	Yes	1.8 kg	Yes	1.2 kg	Yes	150 g	Yes	N/A	Yes	1.96kg	Yes	10kg	No

	WT	Trillium Compact Horizon Info	Value	Score	Artius Info	Value	Score	Episensor Info	Value	Score	Trillium Compact Info	Value	Score
ctrum for high and low frequency	8	.008 - 109 Hz	2	16	0.03 (30 s) – 200	5	40	DC – 200	3	24	0.0083 (120 s) – 108	2	16
rating temperature range - > 150 C	4	-50 - 60C	3	12	-20 - 70	3	12	-20 - 70	3	12	-20 - 60	3	12
/	6	754 V·s/m (±0.5%); 2.4 ng/√Hz @10 Hz	5	30	500 V·s/m; 145 dB DR; low noise	3	18	155 dB DR; noise < 1 ng/√Hz (est.)	4	24	753 V·s/m; 156 dB DR	5	30
nce	5	±2.5 (120 s) / ±10 (20 s)	3	15	±5	5	25	N/A	1	5	±2.5 / ±10	3	15
ployed without direct contact with nment	2	Yes		0	N/A		0	N/A		0	Yes		0
	1	64 GB	5	5	64 GB	5	5	N/A	1	1	64 GB	5	5
collection	3	N/A	1	3	1-1000 sps	5	15	N/A	1	3	N/A	1	3
	7	100 g	5	35	N/A	1	7	100 g	5	35	100 g	5	35
sumption	5	180-120 mW	5	25	600 mW @ 7-16V	3	15	1,2000 mW @ 12V	2	10	180-120 mW	5	25
		Nominal		81	Nominal		115	Nominal		69	Nominal		81

	WT	STRYDE Node Range+ Info	Value	Score	MEMS Seismometer Info	Value	Score	GS-1 Seismometer Info	Value	Score	GeoSIG arolla Info	Value	Score
ctrum for high and low frequency	8	1 – 125	1	8			0	1 - 100Hz	1	8	0.00833 Hz to 50 Hz	2	16
rating temperature range - > 150 C	4	-30 - 70	4	16			0	-40 - 60	4	16	-20 - 60	3	12
/	6	22 ng/√Hz @16 dB	2	12			0	Hiugh sensitivity	4	24	1200V/m/s (±0.5%);	5	30
nce	5	N/A	1	5			0	±2	4	20	±2	4	20
ployed without direct contact with nment	2	N/A		0			0	No	0	0	No	0	0
	1	64 GB	5	5			0	N/A	1	1	N/A	1	1
collection	3	500-1000 sps	3	9			0	N/A	1	3	N/A	1	3
	7	High-shock tolerant	3	21			0	N/A	1	7	810g	5	35
sumption	5	N/A	1	5			0	Passive	4	20	N/A	1	5
		Nominal		55	Nominal		0	Nominal		72	Nominal		82

RTD Trade Study

PERCI Instrument Trade Study: RTDs

Choices / Criteria	Germanium (GR Series)		Platinum (PT-111)		Cernox RTD		Silicon Diode (CY670 Series)			
Must Haves	Info	Y/N	Info	Y/N	Info	Y/N	Info	Y/N	Info	Y/N
Operating Temp Range (within a range of -223.15°C(50K) to -198.15°C (75K)in the body)	1.4K to 100K	Yes	14 K - 1123.15 K options available	Yes	0.1 K - 420 K options available	Yes	1.4 K - 500 K	Yes		
Commercial off the shelf (COTS) Options Available	COTS	Yes	COTS	Yes	COTS	Yes	COTS	Yes		
Low Power Operation (<10 mW)	10^-7 to 10^-6 W from 10K - 100K		10^-5 W from 10K - 100K	Yes	10-7 to 10-6 W from 10K - 100K	Yes	10 µW (10 µA excitation)	Yes		

Wants	WT	Info	Value	Score	Info	Value	Score	Info	Value	Score	Info	Value	Score	Info	Value	Score
Temperature Errors (delta T / T) in Magnetic Field Range of percent. Assigned Value: < 0.1 % 7-10 0.1% - 1.0 % 3-6 > 1.0 %. 1-2	1	-3 <> -20 % (20K) (2.5 T)	1	1	0.04 % (87K) (2.5 T)	4	4	0.002 % (77K) (2.5 T)	10	10	-0.3 % (80K) (2 T) Junction perpindicular to field	6	6			0 0 0
Radiation Resilient (Largest delta T error up to 100K [magnitude])	6	17 mK	5	30	100 mK	4.5778	27.4669	40 mK	4.8830	29.2980	~1000 mK	0	0			0 0 0
Measurement Reproducibility (using 77 K)	10	±0.5 mK reproducibility at 4.2 K, +- 20mK at 77 K	4.6938	46.9387	High Reproducibility: +-5mK at 77K	5	50	±0.5 mK at 4.2 K, ±16 mK at 77 K	4.7755	47.7551	±0.25 K from 2 K to 100 K	0	0			0 0 0
Thermal Response (using 77 K)	7	Thermal response time 200 ms at 4.2 K, 3 s at 77 K	0	0	2.5 s at 77K	0.8369	5.85872	50ms - 1s at 77K based on packaging options (using 250ms SD packaging option)	4.6032	32.2229	BR Model: 1 ms @ 4.2 K, 13 ms @ 77 K,	5	35			0 0 0
Resitive Sensitivity	4										From 25 K to 500 K, a silicon diode has a nearly constant sensitivity of 2.3 mV/K					0 0 0
?	0			0 0 0			0 0 0			0 0 0			0 0 0			0 0 0
?	0			0 0 0			0 0 0			0 0 0			0 0 0			0 0 0
?	0			0 0 0			0 0 0			0 0 0			0 0 0			0 0 0
?	0			0 0 0			0 0 0			0 0 0			0 0 0			0 0 0
Total Score		Minimum Nominal Maximum		0 77.9387 0			0 87.3256 0			0 119.276 0			0 41 0			0 0 0