Final Presentation P.E.A.N.U.T. Team 8

Caroline Kuhnle, Nathaniel Rutkowski,
Christian Schrader, Krystina Waters

AE 4771 Spacecraft and Mission Design | Professor John J. Blandino | 12/10/2020 – B Term 2020

Fair Use Statement

Certain materials are included under the fair use exemption of the U.S. Copyright Law and have been prepared according to the fair use guidelines and are restricted from further use.

Nomenclature and Units

- kg: kilogram
- km: kilometer
- m: meters
- mm: millimeters
- mN: milli-newtons
- mG: milli-gees
- MPa: mega-pascals
- NASA: National Aeronautics and Space Administration
- NEXT-C : NASA's Electrical Xenon Thruster-Commerical
- psia: pounds per square inch
- W: Watts
- C: Celsius
- s: seconds
- LV: Launch Vehicle
- C_3: Characteristic Energy
- ASDS: Autonomous Spaceport Drone Ship
- TRL: Technology Readiness Level
- I_{sp}: Specific Impulse
- ΔV: Change in Velocity
- PPU: Power Processing Unit
- Sol: One day on Mars
- SOI: Sphere of Influence

Methodology

Methodology: Approaching the Problem

- Systematic approach: methodical, repeatable, step-by-step, iterative process
  - Calculated ΔV requirements for mission orbital maneuvers
  - Determine best option for Launch Vehicle based on set mission requirements
  - Determined primary propulsion system as electric propulsion using the calculated ΔV and ion thruster requirements
  - Determined the best options for xenon propellant tanks (number of tanks, tank size)
  - Once the Propulsion Subsystem was designed all other subsystems were added using an iterative process
  - Determined power system that would accommodate the power required for the entire spacecraft
  - Determined the type of actuator and placement of ACS thrusters based off moments required for the spacecraft

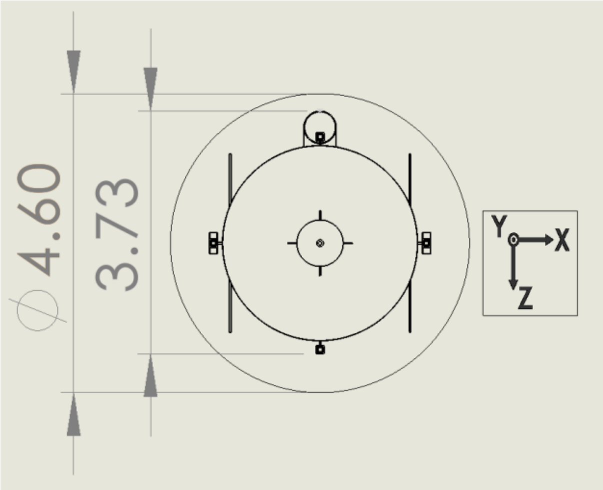
Methodology: Key Figures of Merit

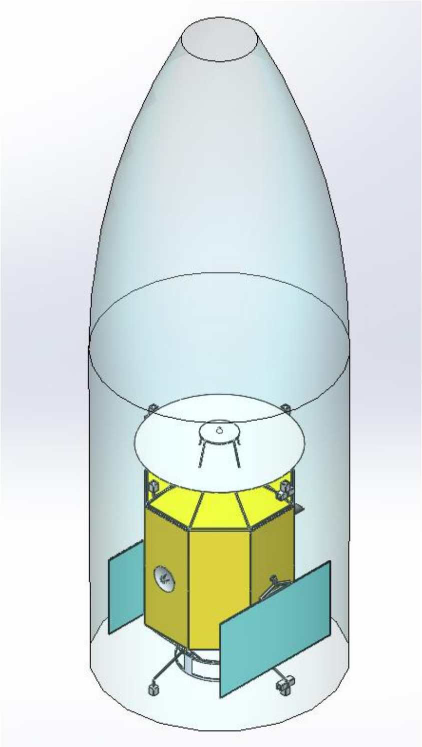
Figure of Merit	Description
Initial Wet Mass	In designing our propulsion system, we aimed to determine a maximum initial wet mass so that we could focus on minimizing our total mass and optimize the weight and accelerations of our spacecraft.
ΔV Requirements	Due to our choice of electric propulsion we needed to ensure we could perform low thrust maneuvers. Understanding and determining these values was important in order to determine our initial wet mass and propellant mass for each stage. We used a paper provided in references to find the necessary ΔV Requirements.
Trip Time	It was important when deciding on a thruster to pick one that did not add a lot of extra mass to the spacecraft but also minimized trip time through provided thrust and mass flow rate.
Minimum Component TRL	We wanted to select components with a minimum TRL value of 6 in order to ensure the reliability and maturity level of each unit of our spacecraft and mission.
Launch Vehicle	We wanted to keep launch costs low and have flexibility in our launch vehicle. The Falcon 9 was chosen because of its lower cost, reusability, and flexibility. This was most important in determining our mass as we could not exceed 1715 or 3240 kg depending on the recovery method.

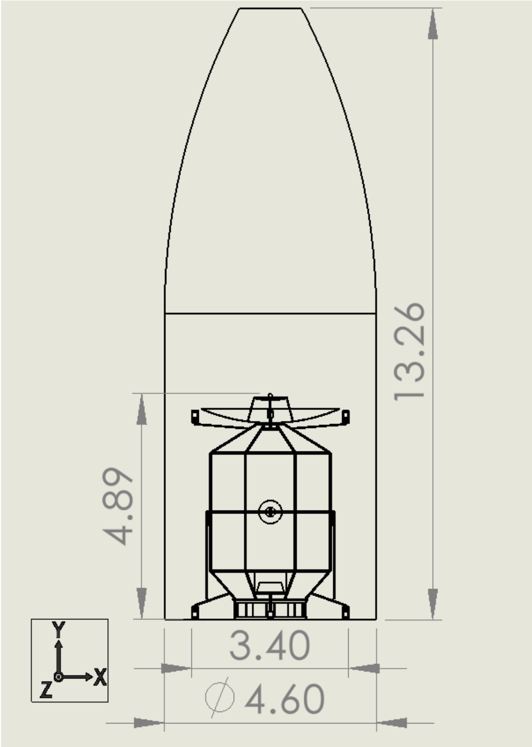
Summary of Design

Summary of Design: Launch Configuration

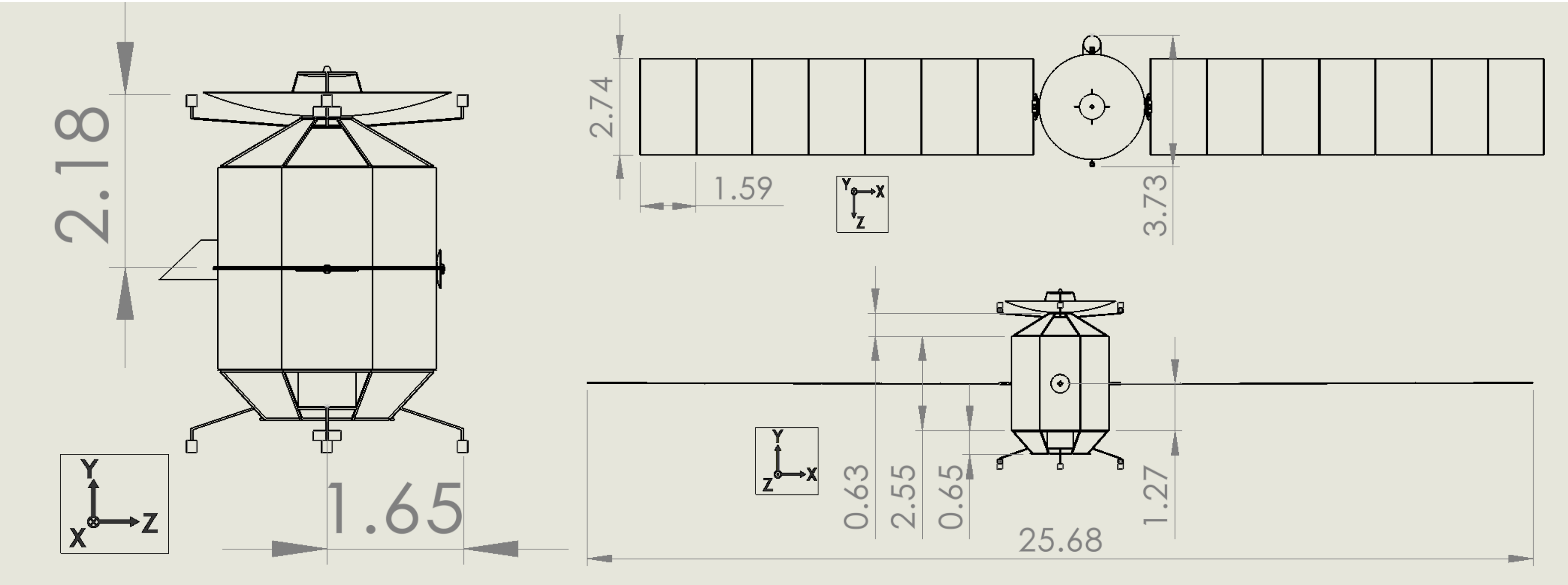
- In launch configuration, the spacecraft fits within the payload fairing of the Falcon 9.





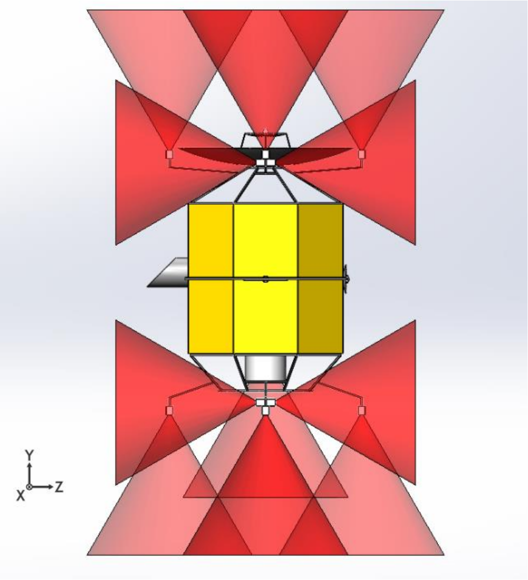


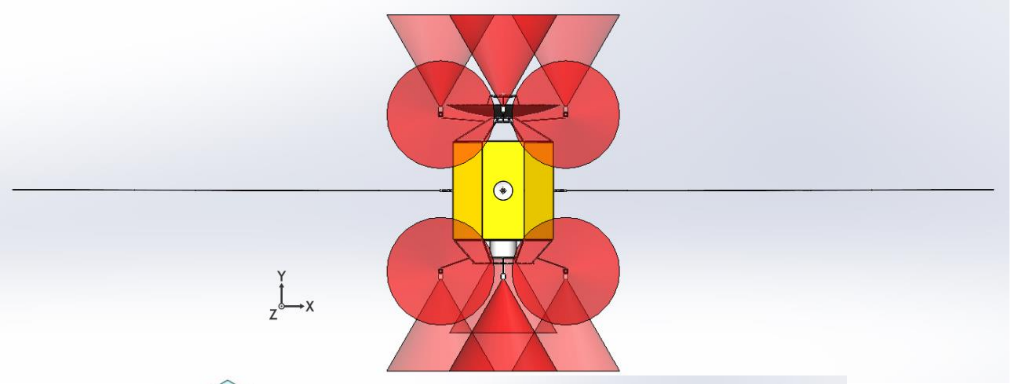
Summary of Design: Cruise/primary mission configuration

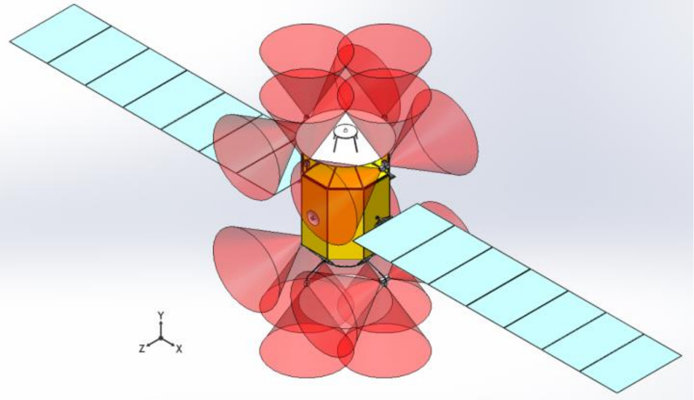


Summary of Design: Cruise/primary mission configuration with ACS plumes

- Thruster plumes of ACS PPTs and NEXT-C do not impinge on any spacecraft surfaces







Summary of Design: Subsystem Mass Breakdown

Component	Mass
Miscellaneous Subsystems	350 kg
Structure	303 kg
Propulsion	1706 kg
Power	744 kg
ACS	62 kg
Total Wet Mass	3165 kg
Payload Adapter	40 kg
Total Mass of Capsule	3205 kg

Summary of Design: Moments of Inertia Calculation

Wet Mass		
	Hand Calculated MOI (kg/m^2)	**SolidWorks MOI (kg/m^2)**
I_{xx}	2992.25	2353.79
I_{yy}	13005.03	13369.36
I_{zz}	13574.12	13777.13
Dry Mass		
	Hand Calculated MOI (kg/m^2)	**SolidWorks MOI (kg/m^2)**
I_{xx}	1750.31	2252.89
I_{yy}	11959.41	13236.19
I_{zz}	12332.18	13609.28

Summary of Design: Launch Vehicle Selection

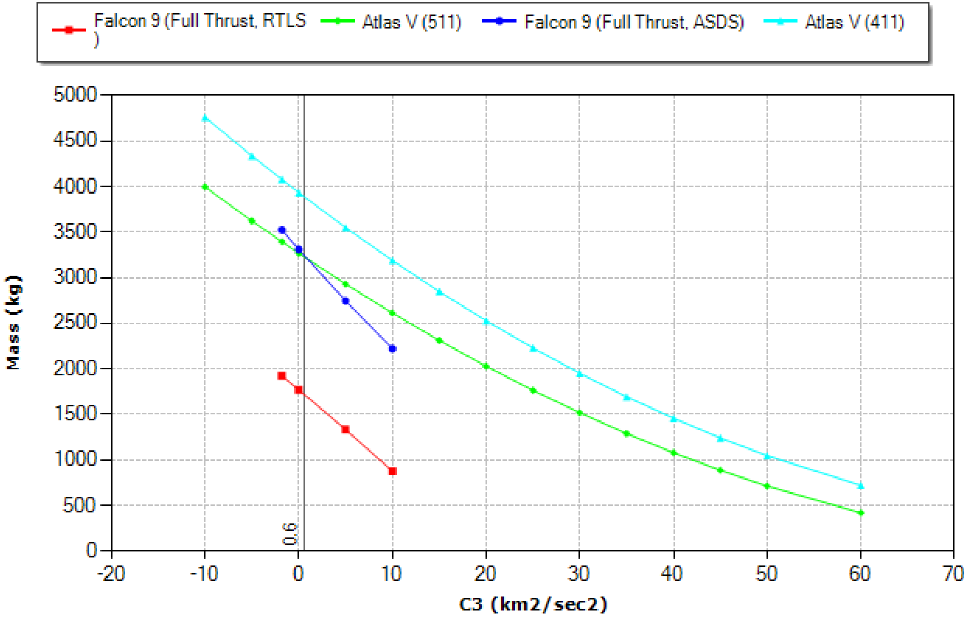
- Launch Vehicle Requirements
  - Required $C_3 = 0.6$ for insertion to Mars transfer orbit
  - Total Launch Mass: 3205 kg

- Vehicle Selection
  - Falcon 9 ASDS, primary
  - Atlas 511, secondary

Falcon 9 Landing on a drone ship in the Atlantic Ocean [3]

Summary of Design: Launch Vehicle Constraints

- Falcon 9 ASDS
  - Max Mass: 3240 kg
  - Fairing ID: 4.6 m
  - Fairing Max Height: 11 m
- Atlas V (511)
  - Mass: 3225 kg
  - Fairing Diameter: 5 m
  - Fairing Height: 9.397 m



High Energy Launch Vehicle Performance for C_3 = 0.6 [2]. Data retrieved from Nasa

Summary of Design: Launch Vehicle Comparison

- Primary Option: Falcon 9 (ASDS)
  - Lower cost: $62 Million new, $50 Million reused
  - 34 Launches in 2019-2020 (34 Successful, 0 Failures)
    - 19 Drone Ship Landings (17 Successful, 2 Failures)
  - Reusability
- Secondary Option: Atlas V (511)
  - Higher cost: $130 Million base price
  - 7 Launches in 2019-2020 (7 Successful, 0 Failures)
    - Note: only 5 were the 5XX configuration
  - Not Reusable

Propulsion Subsystem Design

Propulsion Subsystem Design: Primary selection

- A systematic approach was used for selecting the propulsion technology
- First Different propulsion types were compared
  - Ion Propulsion was selected
- Then ion propulsion systems from different companies were compared
  - NEXT-C for Aerojet Rocket Rocketdyne was selected
- Areas of interest for selecting
  - That the propulsion system mass would not be larger than the mass available for the launch vehicle
  - That the failure free flight time was larger than thruster on time
  - That the thrust to weigh ratio could not excided 0.001 in order to achieve a low thrust transfer

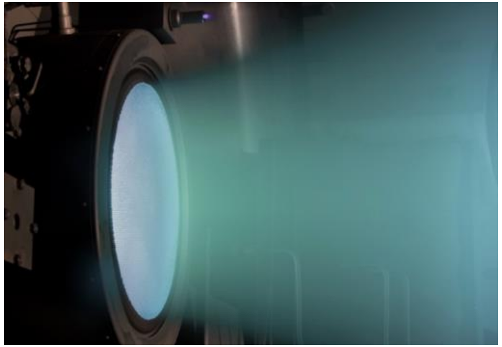
Propulsion Subsystem Design: Mass Breakdown

Component	Mass
Thruster	14 kg
PPU	36 kg
Gimbal	2 kg
PPU Thermal	3 kg
Fixed Feed	10 kg
Feed System	2 kg
Structure	5.9 kg
Subtotal	57.9 kg

Component	Mass
Cabling	2.15 kg
Structure	17.16 kg
Thermal	2.15 kg
Mechanisms	2.15 kg
Propellent Tank	306.90 kg
Total Subsystem Dry Mass	**419.89 kg**
Propellent	1286.43 kg
Total Wet Mass	**1706.32 kg**

Propulsion Subsystem Design: Thruster Selection

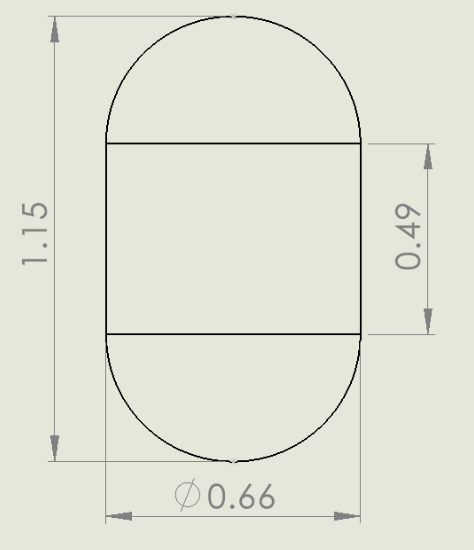
- NEXT-C Description:
  - Type: Ion Propulsion Systems
  - Manufacture: Aerojet Rocketdyne
  - Thruster efficiency: 69%
  - Thrust 235 mN
  - I_{sp}: 1455 s
  - Input Power: 7330 W
  - TRL:6
  - Quantity: 1
- Reasons for selection:
  - Thruster power does not exceed available power
  - Mass is not above available mass for launch vehicle
  - Thrust on time smaller than failure free flight time



NEXT-C Ion Propulsion System [5] from Aerojet Rocketdyne

Propulsion Subsystem Design: Tank Geometry Selection

- Propellant:
  - Material: Xenon
  - Mass: 1286.43 kg
  - Pressure: 31 MPa
  - Temperature: 25 C°
  - Density: 2400 kg/m^3
- Tank:
  - Material: TI-6A1-4V
  - Required Volume: 0.54 m^3
  - Number: 1
  - Shape: Cylindrical Tank with Spherical Endcaps
  - Radius: 0.33 m
  - Length: 1.15 m



Propulsion Subsystem Design: Tank Geometry Selection

- Reasoning behind propellant tank geometry:
  - The team decided on a custom cylindrical tank with Spherical endcaps due to our choice of one ion thruster
  - Custom tank allows flexibility with number of tanks and mass of tank
  - Xenon propellant in tank kept at maximum pressure of 4500 psia or about 30 MPa.

Mission Plan

Mission Plan: Maneuver Specifications

The mission requires four maneuvers to complete.

1. Launch to a C3 = 0.6 km^2/s^2
   - Launch Directly into Hohman Transfer Orbit
   - Assumed to be impulsive
2. Mars capture
   - 5-day elliptical Mars orbit
3. Spiral down to 500 km circular Mars Orbit
4. Spiral up to 5982 km circular Phobos Trailing Orbit

Mission Plan: ΔV Requirements

Maneuver	Thruster	ΔV	Propellant Expended	Thruster On Time
1	Launch Vehicle	Provided by Launch Vehicle	N/A	N/A
2	NEXT-C	2.6 km/s [1]	527.23 kg	370.64 days
3	NEXT-C	2.8 km/s [1]	470.03 kg	330.43 days
4	NEXT-C	1.18 km/s	172.03 kg	139.12 days
	Total	**6.58 km/s**	**1169.29 kg**	**840.19 days**

Mission Plan: ΔV Requirements Cont..

	Starting Thrust	Ending Thrust	Starting Acceleration	Ending Acceleration
1	N/A	N/A	N/A	N/A
2	235 mN	235 mN	.00757 mG	.00908 mG
3	235 mN	235 mN	.00908 mG	.01105 mG
4	235 mN	235 mN	.01105 mG	.01200 mG

- Thrust remains constant throughout mission

Mission Plan: Phases

Phase	Name	Description	Length
1	Maneuver 1	Launch from Earth's surface	N/A
2	Departure	Coast to edge of Earth's SOI	7.04
3	Hohman Transfer	Transfer from Earth to Mars	258.86
4	Maneuver 2	Mars capture	370.64
5	Maneuver 3	Spiral to Mars Science orbit	330.43
6	Mars Science	Spend 30 Sols on Mars Science	30.82
7	Maneuver 4	Spiral to Phobos Trailing Orbit	139.12
8	Phobos Science	Spend 670 Sols on Phobos Science	688.42
		Total Mission Lifetime:	**1825.34 days (≈5 years)**

Power Subsystem Design

Power Subsystem Design: Mass Breakdown

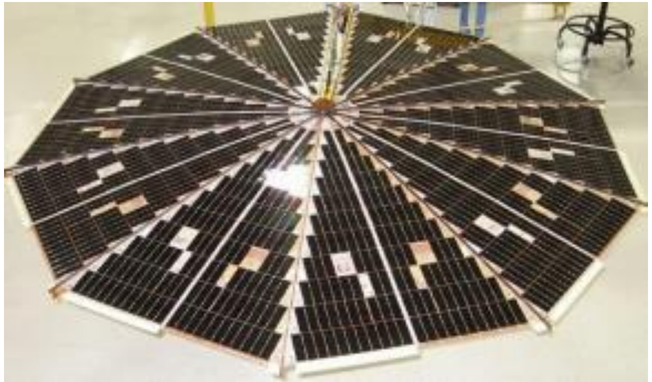
Component	Mass
Solar Array	183.79 kg
Battery Mass	12.35 kg
Power Control Unit	223.14 kg
Regulators/ Converters	278.93 kg
Wiring	46.15 kg
Total Subsystem Mass	**744.36 kg**

Power Subsystem Design: Power Budget

Purpose	Required Power	Cumulative Time Required	Satisfies Requirement
Primary Propulsion and Inactive Payload	7630 W	840.18 days	Yes
Active Science Collection	1500 W	719.24 days	Yes
Repointing/Deadband repointing	210 –600 W	1825 days	Yes

Power Subsystem Design: Component Selection

- Multijunction Phoenix Ultra Flex Array
  - high performance in comparison to other types of panels
  - high-power requirements of the selected thruster.
  - The theoretical efficiency for this type of solar array is 28.3%.
  - TRL 9
  - BOL Output(1.5 AU): 11,157 W
  - EOL Output(1.5 AU): 9,638 W

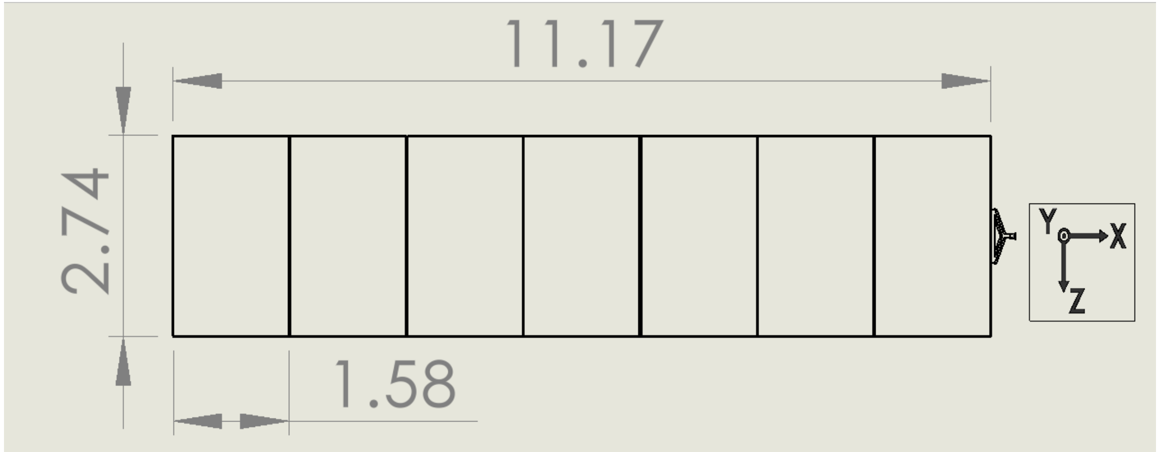


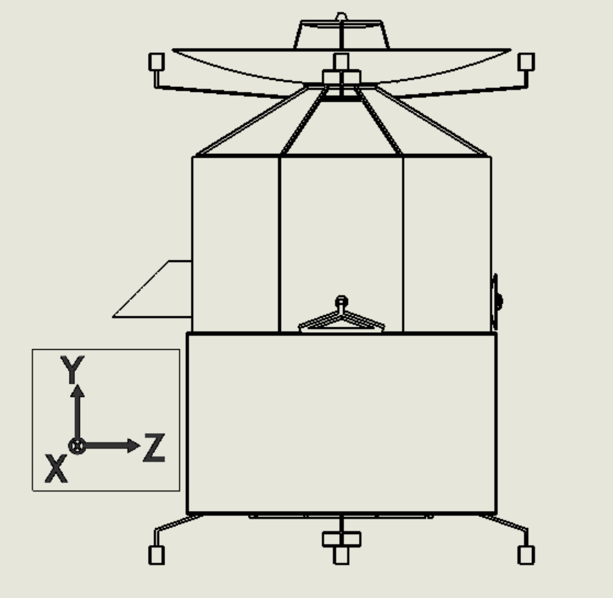
Power Subsystem Design: Component Selection

- The team ultimately chose Nickle Hydrogen (NiH2) batteries due to their high specific energy density and depth of discharge capabilities compared to that of NiCd.
  - DoD: 45% based on Fig 11-11 in SMAD handout Electric Propulsion #2
  - TRL: 9
  - Specific Energy Desnity: 40 W-hr/kg

Power Subsystem Design: Solar Array Geometry

- 61.3 m^2 of solar panels are required.
- 2 arrays of 7 segments are used.





ACS Subsystem Design

ACS Subsystem Design: Detailed Mass Summary

Component	Mass
PRS-101 PPT (x16)	48 kg
HR12 Reaction Wheels (x2)	14 kg
Total Mass	**62 kg**

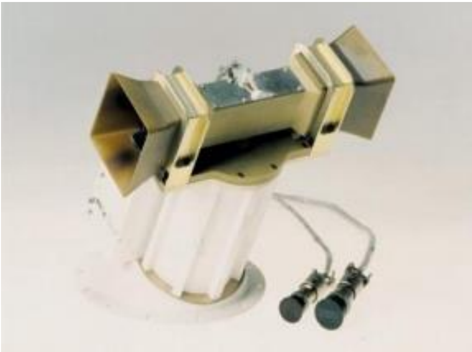
ACS Subsystem Design: Reaction Wheel Selection

- Use reaction wheels for 10-minute, 180 degree slew maneuvers
  - Require higher torque & angular impulse to complete
  - Don’t require separate fuel tank
- 2 Honeywell HR12-25 Reaction Wheels
  - Mounted to provide torque for slew about pitch axis
  - Selected for lower weight, 2x with 1 for redundancy
  - Redundancy not possible after MOI calculated from SW
- Angular Impulse: 25 N-m-s, each
- Max Torque: 0.4 N-m, each
- Mass: 7 kg, each
- TRL: 9
- Power at Max Torque: 105 W, each

HR12-25 [6]
©Honeywell Aerospace 2003

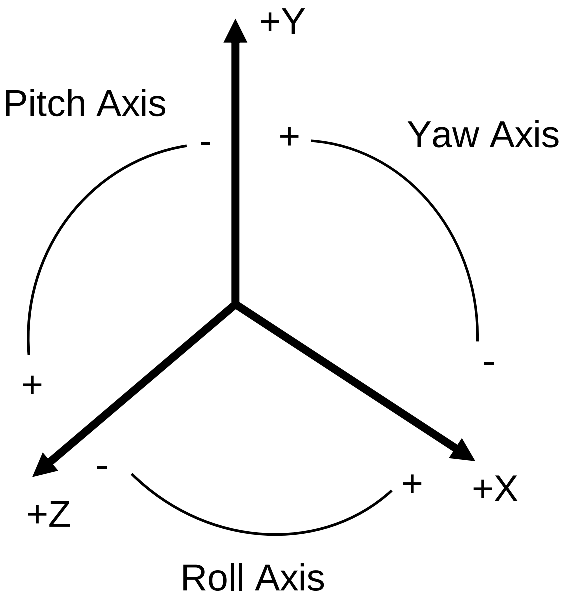
ACS Subsystem Design: PPT Selection

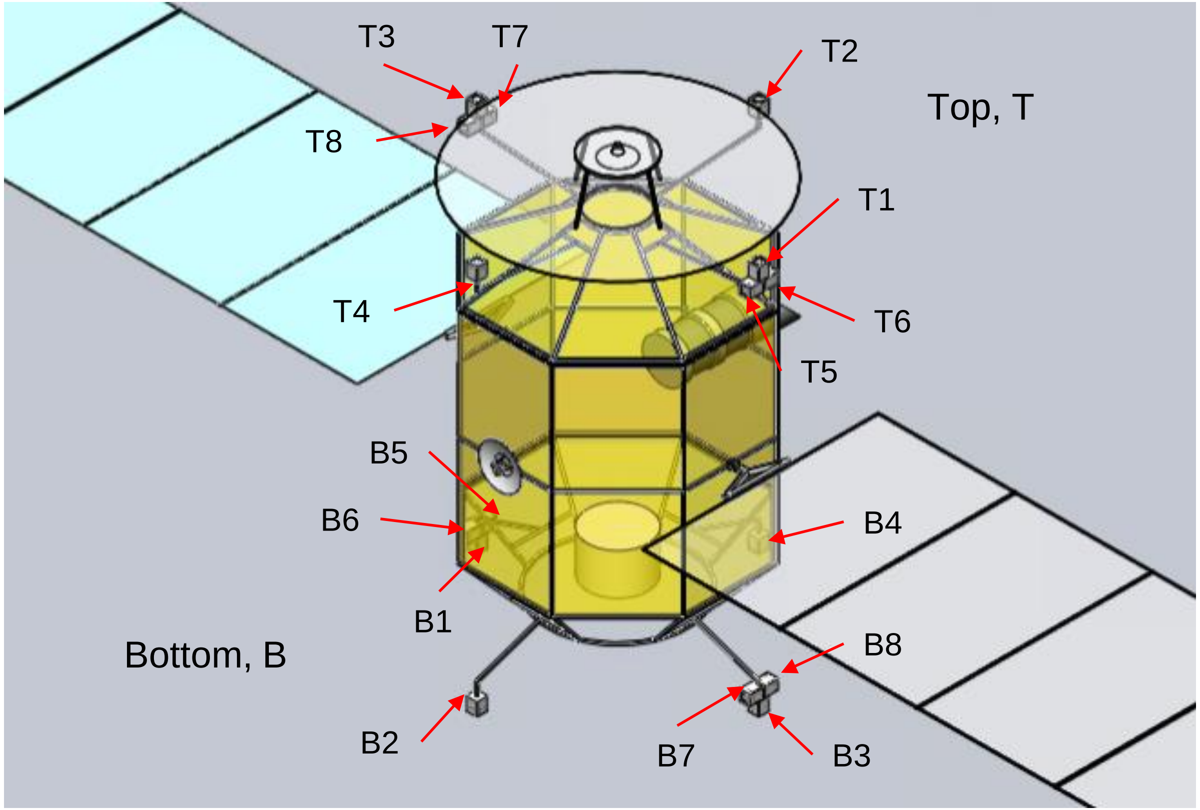
- Use PPTs for maintaining 10 to 30-minute deadband angle
  - Don’t require separate fuel tank, uses Teflon® bar
- 16 PRS-101 Pulse-Plasma Thrusters
  - Yaw: x2 thrusters in clockwise and counterclockwise direction
  - Pitch: x6 thrusters in clockwise and counterclockwise direction
  - Roll: x4 thrusters in clockwise and counterclockwise direction
- Thrust: 1.24 mN
- Impulse: 3,000 N-s, demonstrated per thruster
- Minimum Impulse Bit: 0.1 mN-s, each
- Mass: 3 kg, each
- TRL: 9
- Power: 100 W, each



PRS-101 [7]

ACS Subsystem Design: Geometry





ACS Subsystem Design: Thruster Logic Table

	Top								Bottom							
Thruster Number	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Yaw (Z)	-		+						-		+					
Pitch (X)		-		+	-	+	+	-		-		+	-	+	+	-
Roll (Y)					+	-	+	-					+	-	+	-

ACS Subsystem Design: Reaction Wheel Performance

180 deg Slew Maneuver	Value
Moment of Inertia	2353.79 kg-m^2
Actuation Time	15.81 s
Coast Fraction	0.947
Coast Time	568.37 s
Angular Impulse	25.32 N-m-s
Required Torque	0.8 N-m
Required Power	210 W
Angular Acceleration	0.00034 rad/s^2
Peak Angular Rate	0.005377 rad/s

ACS Subsystem Design: PPT Performance

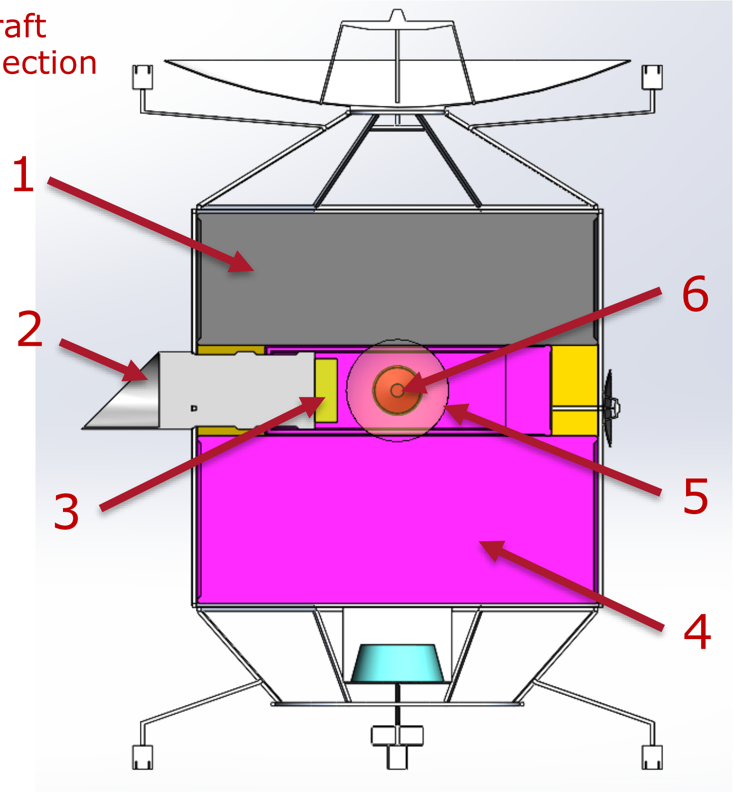
5 mrad Deadband	Value
Moment of Inertia	2353.79 kg-m^2
Thruster Moment Arm	1.96 m
Minimum Ibit	20.4 mN-s
Residual Angular Rate	0.000159 rev/min
Deadband Half Angle	0.143235 deg
Angular Rate, after pulsing	3.204E-07 rad/s
Quiet Time	255 min
Required Power	600 W

Mechanical Subsystem Design

Mechanical Subsystem Design: Internal Components

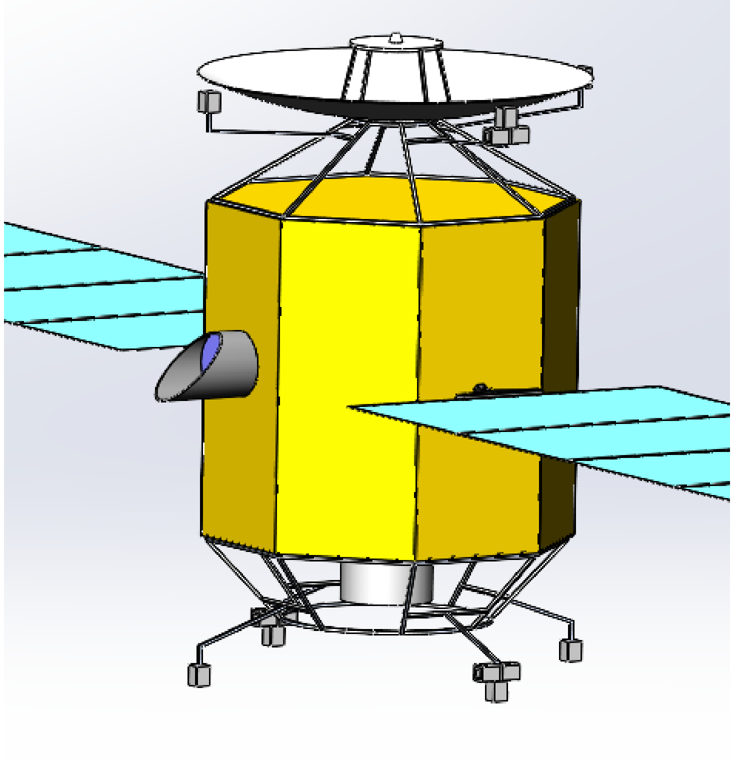
1. Misc. Subsystems
   – $\rho = 75\frac{kg}{m^3}$ is assumed.
2. HiRISE Payload
3. NEXT-C PPU
4. Power Subsystem
   – $\rho = 75\frac{kg}{m^3}$ is assumed.
5. Xenon Tank
   – Show transparent to show reaction wheel behind it.
6. Reaction Wheel

Spacecraft Cross-Section



Mechanical Subsystem Design: Geometry

- The bus has a side length of 1.1 m and a height of 2.55 m.
- The total surface area of 33.4 m^2.
- Using an area specific mass of 9.1 kg/m^2, the Mechanical Subsystem has a mass of 303.94 kg.



Conclusion

Conclusion: Overcoming Challenges

- Our first main challenge was once we decided we wanted to go with electric propulsion, figuring out how to perform a low thrust segment analysis to determine the ΔV Requirements at each phase during our mission.
- The next obstacle the team faced was when the original thruster selected for the team’s PDR no longer met the mission requirements of the project. Changing thrusters required a lot of recalculating values and some complications when designing a power system that could provide the large amount of power required for the new thruster.
- As different subsystem masses were confirmed we spent a significant amount of time iterating to get our launch mass below the 3240 kg limit of the launch vehicle

Conclusion: Discussion

- The team may "expand the trade space" by continuing to analyze the resource availability, costs and provisioning of electric propulsion systems and ion thrusters. In addition, the team could reduce or extend the time spent at target Phobos orbit, reduce propellant mass by reducing the time spent orbiting Phobos, or bring more payloads to do more science.

- A constraint we chose to relax is our TRL expectations. We do not necessarily have to have every component at a TRL value of 9. We could achieve benefits such as lower trip time or higher thrust and accelerations by using experimental thrusters.

Thank you

References

- [1] Brophy, J., & Rodgers, D.*Ion propulsion for a mars sample return mission.* (). Pasadena California:

  Retrieved from https://trs.jpl.nasa.gov/bitstream/handle/2014/15789/00-1530.pdf?sequence=1&isAllowed=y
- [2] Carney, M., & Haddox, E. (2020). Launch vehicle performance website. Retrieved from https://elvperf.ksc.nasa.gov/Pages/Default.aspx
- [3] Official space X photos. (2017). Retrieved from https://www.flickr.com/photos/spacex/50085443052/
- [4] Wertz, J., & Larson, W. (Eds.).*Space mission analysis and design* (3e ed.) Microcosm Press,

  Kluwer Academic Publishers.
- [5] NEXT–C Overview.*NASA's evolutionary xenon Thruster–Commerical (NEXT–C)*
- [6] Economical.Constellation series reaction wheels. Retrieved from https://satcatalog.com/datasheet/Honeywell%20-%20HR12-50.pdf
- [7] Types of thrusters. (2006). Retrieved from https://www.rocket.com/sites/default/files/documents/Capabilities/PDFs/Electric%20Propulsion%20Data%20Sheets.pdf

Work Distribution

Team Member	Launch Vehicle Selection	Propulsion System Selection	Tank Selection	Propulsion Subsystem Mass Breakdown
Caroline		X	X	X
Max				
Nathaniel	X			
Krys				

Team Member	Thruster Selection	ΔV Requirements	Power System Selection	Solar Array Selection	Power and Mass Budget
Caroline	X				
Max		X			
Nathaniel					
Krys			X	X	X

Work Distribution Cont.

Team Member	MOI Calculations	Full Spacecraft Mass Breakdown	ACS Subsystem Design	Actuator Selection	Logic Table
Caroline		X			
Max	X				
Nathaniel	X		X	X	X
Krys					

Team Member	CAD Drawings	Mech Subsystem Design	Methodology	Conclusion	References/ Editing
Caroline					
Max	X	X			
Nathaniel					
Krys			X	X	X