May 8, 2018

Deep Space 9

Potential Next Mars Orbiter Secondary Payload Study

NASA JPL

COLLEGE OF ENGINEERING
CLIMATE & SPACE
UNIVERSITY OF MICHIGAN

Introduction and Acknowledgements

- This concept study was developed as an educational exercise for UM students , as part of a year-long SURP collaboration, with the goal of providing them exposure to a real-world mission concept

- The Next Mars Orbiter (NeMO) mission concept was selected as the context for this study to provide realistic boundary-conditions in early 2017
  - All allocations provided to the DS9 team were based on reasonable assumptions about what the NeMO excess capacity might be; they were pre-decisional and were for planning and discussion purposes only

- At JPL, the SURP effort was supported by Adrian Arteaga-Garcia, Serina Diniega, Annie Marinan, Danielle Marsh, Austin Nicolas and Bogdan Oaida

- At UM, the SURP effort was supported by Prof. Nilton Renno, Prof. Jamie Cutler, and Prof. Peter Washabaugh, and the AEROSP/SPACE 582/583 students: Sanskar Bhattacharya, Takumi Date, Robyn Hinchman, Brandon Hing, Tzu-Hsiang Lin, Giancarlo Mayor, Sunil Raghuraman, Tatiana Roy, Tod Schulter, Dan Spatcher, David Sweeney, Steven West, and Nathan Williams.

Mission Overview - Objective and Constraints

- **Objective**: Develop secondary payload for potential Next Mars Orbiter (NeMO) concept

Table 1: Breakdown of primary design constraints imposed by NeMO

Category	Provided Requirements
Size	< 1 m x 1 m x 0.5 m (0.5 m^3)
Mass	< 200 kg
Power	< 5 W
Data	< 5 Gbit/day at <10 Mbps

- **Solution:** A cost-effective distributed CubeSat architecture to accomplish science goals

Mission Overview - Science Goals

From MEPAG Decadal Survey:

- Identify processes which control past and current Martian climate
  - Distribution of dust, water/CO_2 clouds
  - Exchange of dust between surface and atmosphere
  - Track pressure, temperature, wind speed
  - Apply data to models of past Martian atmosphere
- Understand how the Martian climate may relate to that of other planets
- Obtain knowledge of Mars sufficient to design and implement a human mission to the Martian surface

For planning and discussion purposes only.

DS9 Mission Concept Overview

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Concept Overview

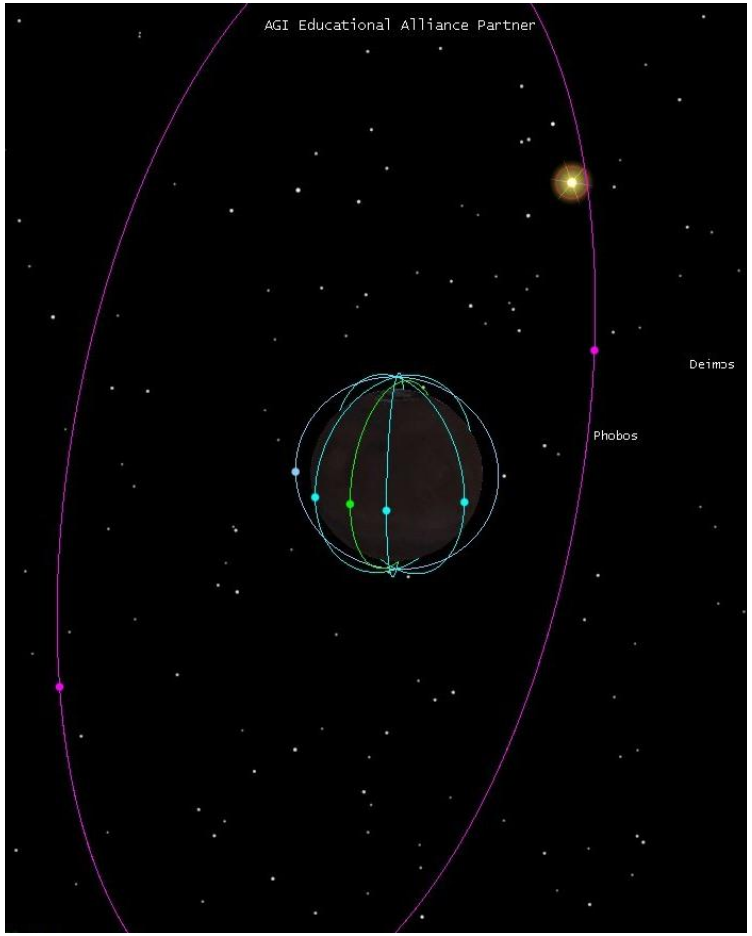
- 6 CubeSats in total to complete science objectives
  - Four satellites in four 600 km orbits to perform multispectral imaging
  - Two satellites in one 20,000 km orbit to initiate radio occultation (RO)

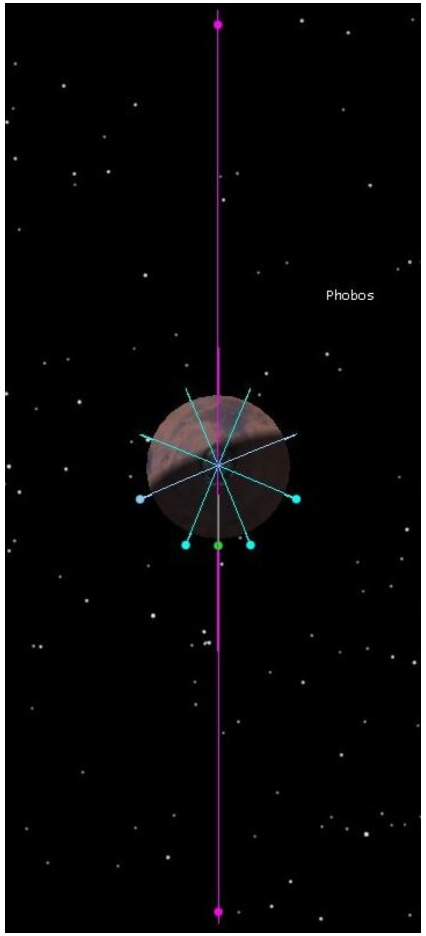
Payload Overview

- Wide angle weather camera (140° FOV) with multispectral imaging capabilities (NIR, Vis, UV)
- RO Science performed using an X-band communications system with a high heritage ultra-stable oscillator from APL

Key Capabilities

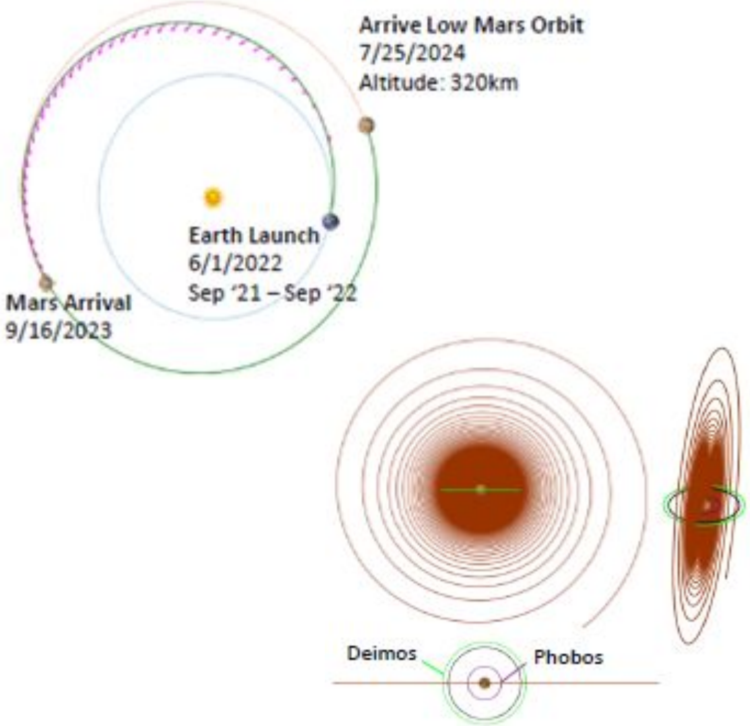
- Imaging:
  - Global coverage with ~2 hour revisit time
  - 1.5 km/pixel resolution at Nadir
- Radio Occultation:
  - 108 RO opportunities per day
  - 100-400 m vertical resolution for atmospheric profiling of T, P, and ρ
  - 4 m/s resolution for wind velocity extrapolations

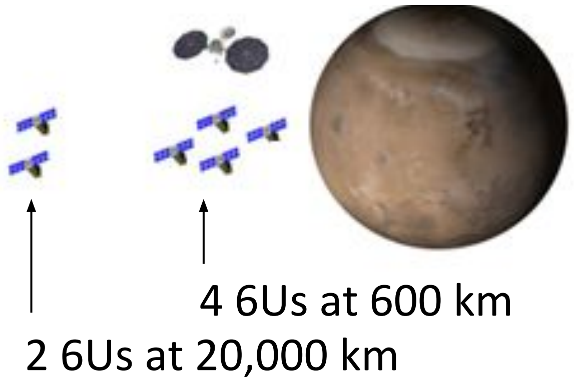


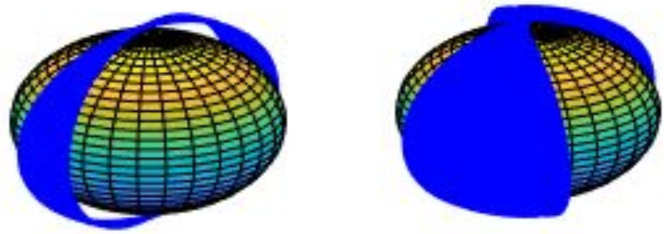


Mission Timeline

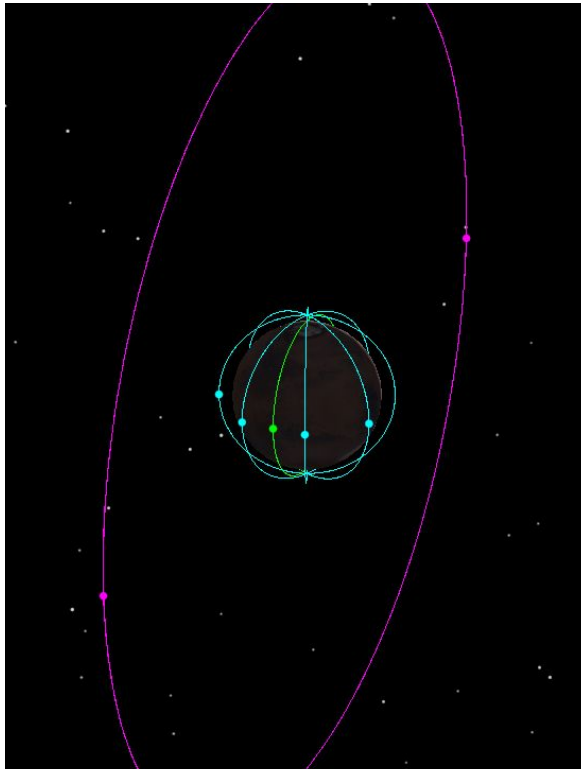
	2022	2023	2024	2025	2026	2027	2028
NeMO	Earth to Mars	Spiral In	Nominal Operations				Mission End
	Hibernation		Deployment; Nominal Operations			Mission End	
	Launch (7/2022)		Deploy Outer 6U's (2/2024)			End of Life (1/2027)	
			Deploy Inner 6U's (6/2024)				
			22.5° RAAN Change Achieved (Inner), 180° Phase Shift Achieved (Outer) (8/2024)				
DS9				67.5° RAAN Change Achieved (Inner) (1/2025)			







22.5° RAAN Change 67.5° RAAN Change



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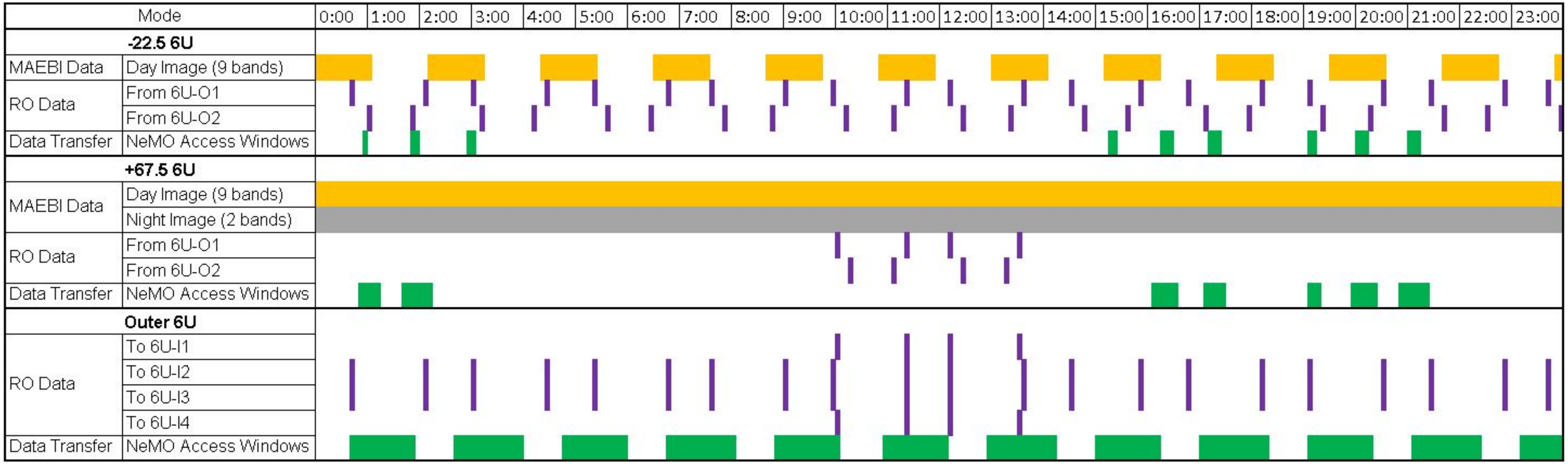
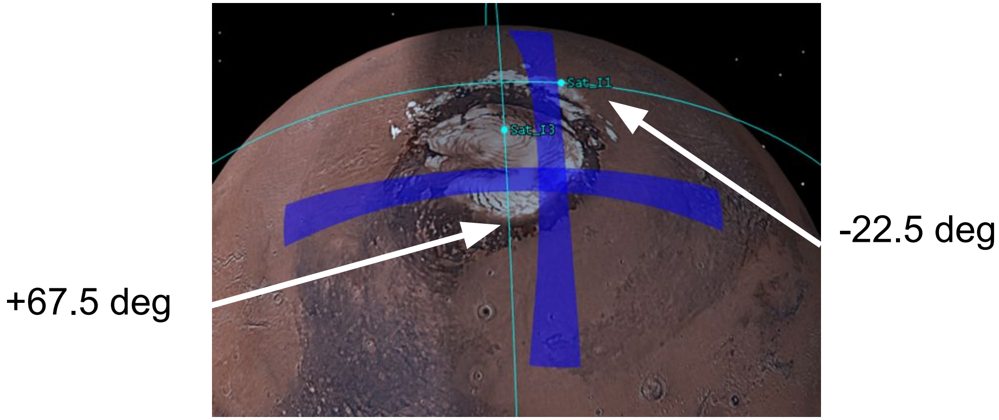
Day in the Life

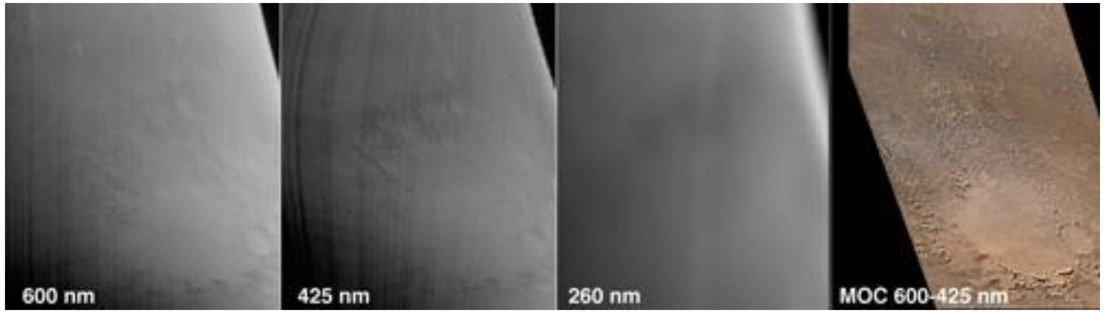




Payload - Multispectral Imaging

Multispectral Imager requirements stem from aforementioned science goals and can be met by MAEBI (MArs Extended Bandwidth Imager)

Science Goal	Requirements	Specification
Track movement of ozone (negatively correlated with H_2O)	UV Spectrum Bands	280, 315 nm
Track Seasonal frost changes at poles	Near Infrared Spectrum bands	1.25 µm, 1.435 µm
Track movements of clouds (CO_2 and H_2O)	Visible Spectrum bands	453, 561, 614, 636, 765 nm
	Global coverage w/ ~2 hr revisit	140° FOV (1,536 x 19.2 km @600 km)
	1.5 km/pixel resolution at Nadir	1.5 km/pixel res. (Nadir @600 km)



For planning and discussion purposes only.

Radio Occultation

Overview: This mission provides many opportunities to perform Radio Occultation (RO), an atmospheric data collection technique performed using X-band transmission through an atmosphere to characterize temperature, pressure, and density in order to meet the aforementioned science goals

Component Selected: **[1] Iris V2.0* (High TRL, high heritage component by JPL)**
[2] MGA 4x4 Tx Patch Array (Iris V2.0 recommended patch array)

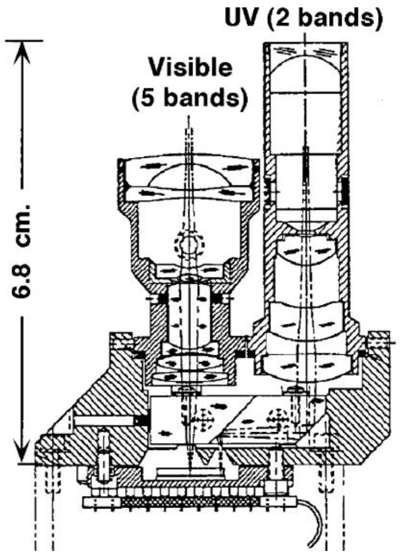
Requirements	Specification
X-band transmitter and receiver	Transmitting over X-band **[1] [2]**
High-precision position and velocity knowledge	ITAR restrictions prevent access to knowledge needed for requirement derivation
Size	0.5 U
Mass	1270 g
Power	0.5 - 35 W

* Anticipated Performance Based on Iris V1.0

Payload - Multispectral Imaging

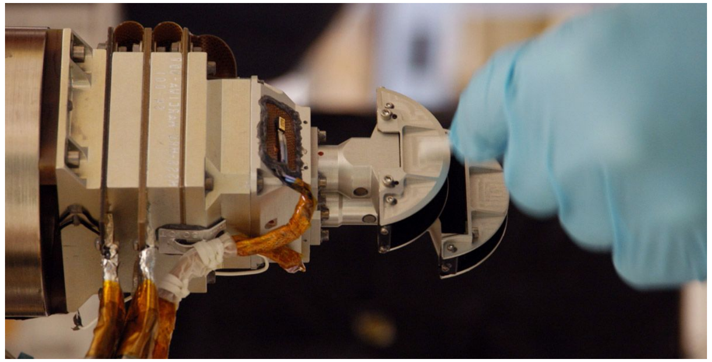
MAEBI

- Updated MARCI (Mars Color Imager) developed by Malin Space Science Systems
- Adding 2 IR bands to satisfy science goals (CO2 and H2O detection)
- Operational heritage on Mars Reconnaissance Orbiter (MRO)



Original MARCI Configuration

Instrument	MAEBI
Total Mass	0.53 kg
Dimensions	5 x 8.6 x 11.2 cm
Power Required	2 W - Operating 0.1 W - Standby
Cost Estimate	$5,000,000



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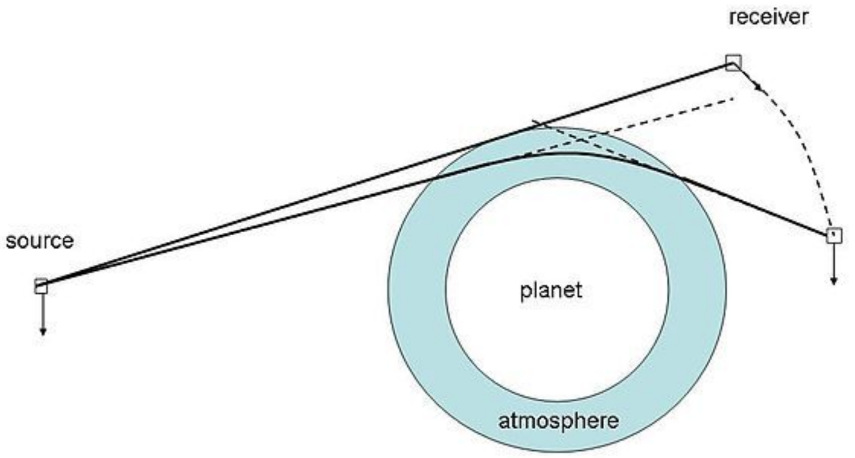
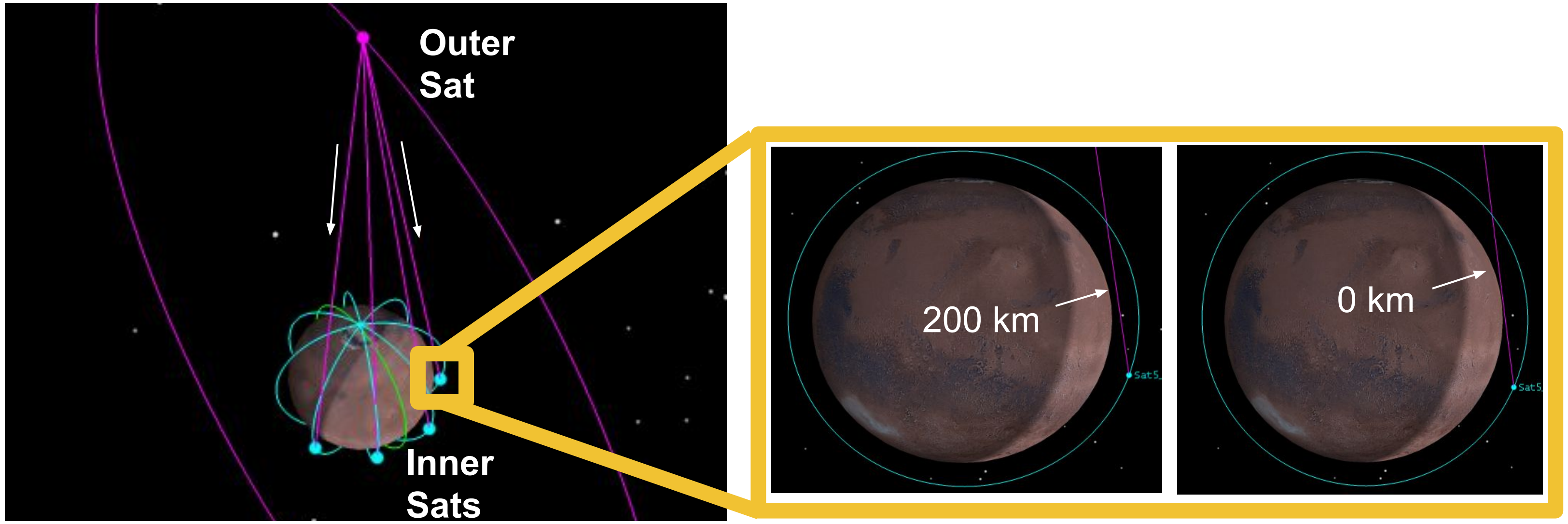
Radio Occultation

Uses communication signals to measure refractivity of the atmosphere
- Can determine accurate measure of wind speed, density, pressure, and temperature
- Requires high-precision position and velocity knowledge and X-band transmitter/receiver

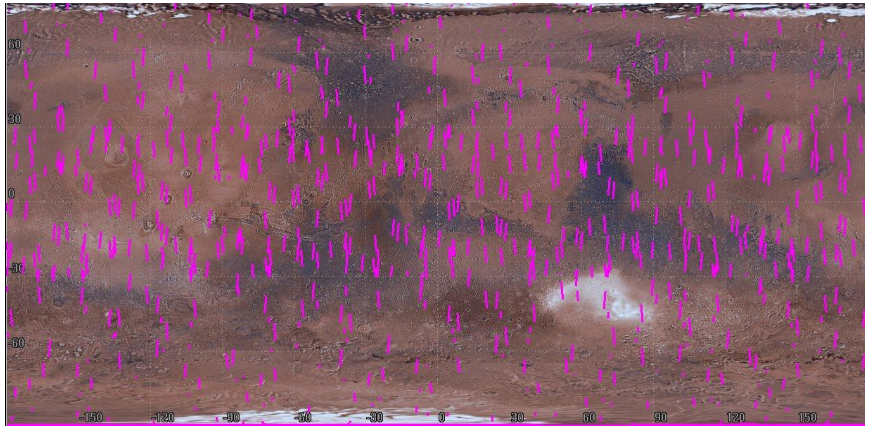
RO opportunity defined as:
- Atmosphere lies between communicating spacecraft
- LOS between communicating spacecraft based on 70 deg antenna beamwidth

DS9 provides:
- RO window durations between 20 seconds and 2.5 minutes
- 108 RO opportunities per day when transmitting from Outer CubeSats to Inner CubeSats





RO Opportunity distribution over 1 Week



Structures Overview

Overview: Structures contains the CubeSat structure itself that holds the satellite components as well as the PPOD used to store the satellite during launch and dispense into Mars orbit.

Component Selected: **[1] ISIS 6U CubeSat Structure**
[2] Planetary Systems Corporation Canisterized Satellite Dispenser

Requirements	Specification	Margin
The PPOD mass, with contained Cubesats, shall not exceed 200 kg.	90.2 kg **[1] [2]**	109.8 kg
PPOD volume shall not exceed 1m x 1m x 0.5m (500,000 cm^3)	69815 cm^3 **[2]**	430,000 cm^3
CubeSat Structure shall meet Cal Poly CubeSat Specifications	-	-

Guidance, Navigation, & Control Overview

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Overview: GN&C provides the sensors and the control actuators to maintain the spacecraft nadir pointing orientation for imaging and pointing for communications/RO opportunities between other spacecraft

Component Selected: **[1] Nano-SSOC-A60 Analog Sun Sensor**
[2] Epson M-G370
[3] BCT XACT
[4] Aerojet MPS-130

Requirements	Specification	Margin
Determine S/C orientation within 0.5 deg	<0.5 deg resolution [1]	-
Provide a pointing accuracy of 0.5 deg	0.003 deg (2 axes), 0.007 deg (3rd axis) [3]	0.493 deg
Attitude Control System (ACS) shall produce a slew rate of 1.5 deg/sec	35.3 deg/s (max) [3]	33.8 deg/s
ACS thrusters shall provide 3.3 mN of thrust	1.25N for each. total 5N (max) [4]	-
ACS shall provide 1.7×10^-4 Nm of torque	4 mNm [3]	235%
ACS shall store 2.3×10^-4 Nms of momentum	15 mNms [3]	650%

Communications Overview

Communications involves data transfer between the Inner and Outer CubeSats and from Inner CubeSats to NeMO.

Components Selected: **[1] Iris V2.0* (High TRL, high heritage component by JPL)**
[2] MGA 4x4 Tx Patch Array (Iris V2.0 recommended patch array)

Requirement	Specification	Margin
Comms system shall use a X-band or UHF band for communication	X-Band at 8.2 GHz [1] [2]	-
Comms system shall provide a minimum data rate of 0.16 Mbps and a maximum of 10 Mbps	Average Data rate from Link Budget: 1.1920 Mbps. [1] Maximum Data rate: 2.7778 Mbps	-
Comms system shall operate maximum of 25 W of power.	Maximum of 9.22 W [1]	171%
Comms Radio system shall provide X-band communications at a range of 27,000 km.	Range requirement satisfied with sufficient data rate [1]	3.035 dB
Comms system shall provide service for a minimum period of 3 years	Iris V2.0 has high TRL and a lifetime over 3 years [1]	**
Antennas to be mounted on the exterior of the CubeSat	Placed exterior, 10 x 10 cm area and has 16 dBi gain [2]	-

* Anticipated Performance Based on Iris V1.0
** Referencing Iris V2.0 Spec sheet ~ 3 years with margin

Thermal Overview

Overview: The thermal system regulates the internal temperature of the spacecraft to maintain the battery battery temperature (driving requirement) to within operating range

Component Selected: **[1] Polyimide Film Insulated Flexible Heater**
[2] Thin Plate Heat Switch

Requirements	Thermal Specification	Margin
Thermal control system shall sustain an internal temperature range, -10 to 30 °C.	Operating temperature range, -5 to 25 °C **[1][2]**	5°C
In stowed configuration, the thermal control system shall prevent thermal leakage greater than 0.1 W to and from NeMO.	- During transit, CDH emit 0.5W one time in day thus leakage is neglectable.	-
Heater Power	Outer orbit: 4.82W, Inner Orbit 0.37W **[1][2]**	-

Command & Data Handling Overview

Overview: The CDH subsystem provides the main processor and controller for the various subsystems and satellite, processing multispectral imaging and radio occultation data for transmission.

Component Selected: Space Micro Proton 200k Lite

Requirements	Space Micro Proton 200k Lite Specification	Margin
In stowed configuration, the CDH system shall send less than 1 Mbps max, and 50 kbps average to NeMO.	264 MBps/2112 Mbps (Max Possible)	-
The CDH system shall be able to store 9.34 Gb	32 Gb	22.66 Gb
The CDH system shall be able to interface with all necessary electrical hardware.	Does interface with all	-
The CDH system shall be able to process 10Gb of science data between access windows (0.115 MBps)	264 MBps (Max Possible)	260 MBps
The spacecraft shall withstand a total radiation dosage of 16060 mrad.	30 krad	29000 rad

Propulsion Overview

Overview: The propulsion system provides the delta-v required during Mars orbital maneuvers and for momentum dumping during imaging (nadir-pointing) attitude maintenance.

Component Selected: Aerojet Rocketdyne MPS-130

Requirements	Aerojet Rocketdyne MPS-130 Specification	Margin
Propulsion system shall be capable of changing the RAAN of a 6U cubesat by 67.5 deg in less than 2 years.	206 day (249 m/s)	524 days
Propulsion system shall use no more than 97 W of power.	31 W	66 W
Propulsion system shall weigh no more than 4.9 kg.	2.76 kg	2.14 kg
Propulsion system shall take up no more than 3U in volume.	2U	33.3%

Electrical Power System Overview

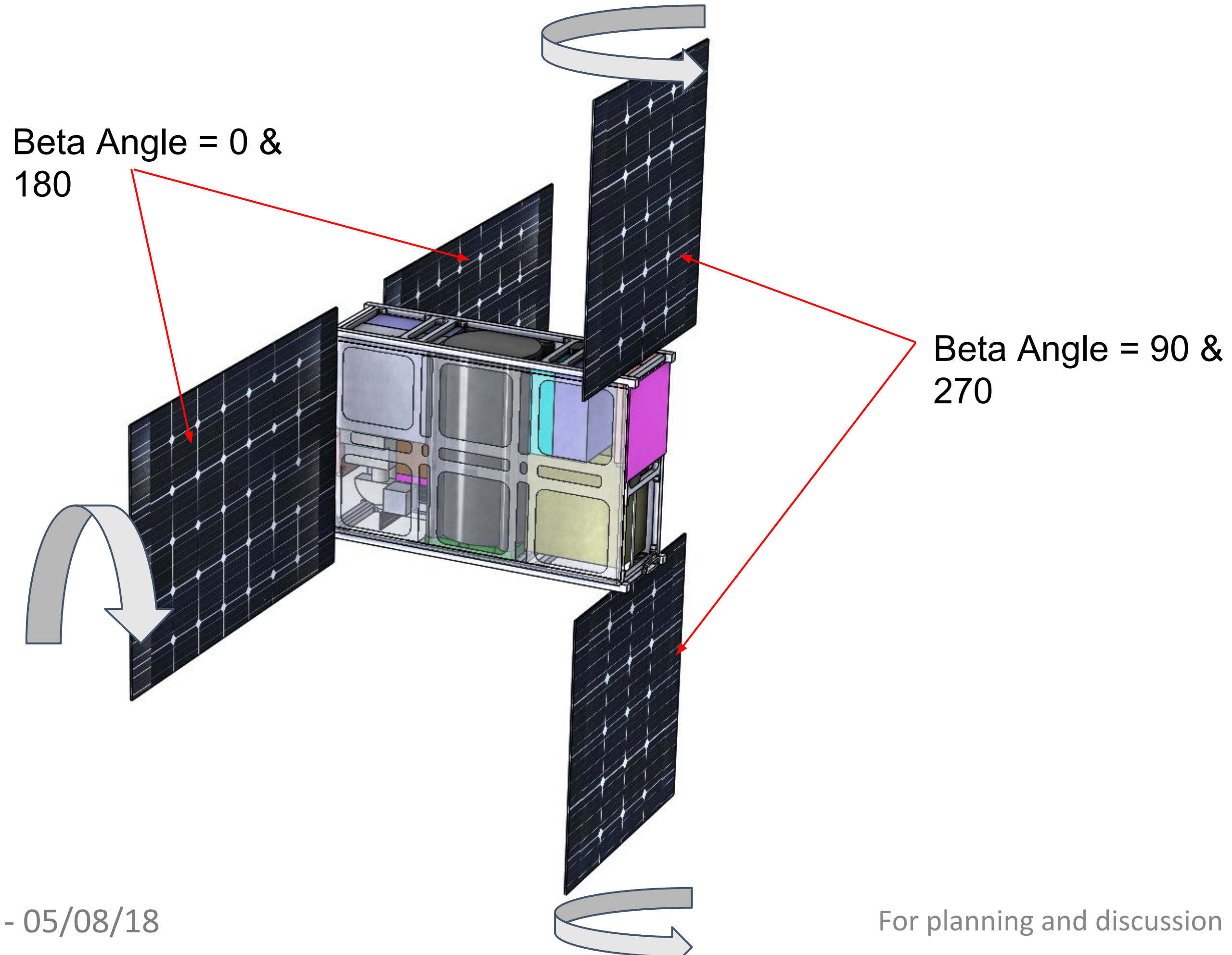
Overview: The EPS subsystem generates power using deployable and body mounted solar arrays for the science instruments and satellite components, and it stores power using two batteries. A power regulator regulates the power to the various components.

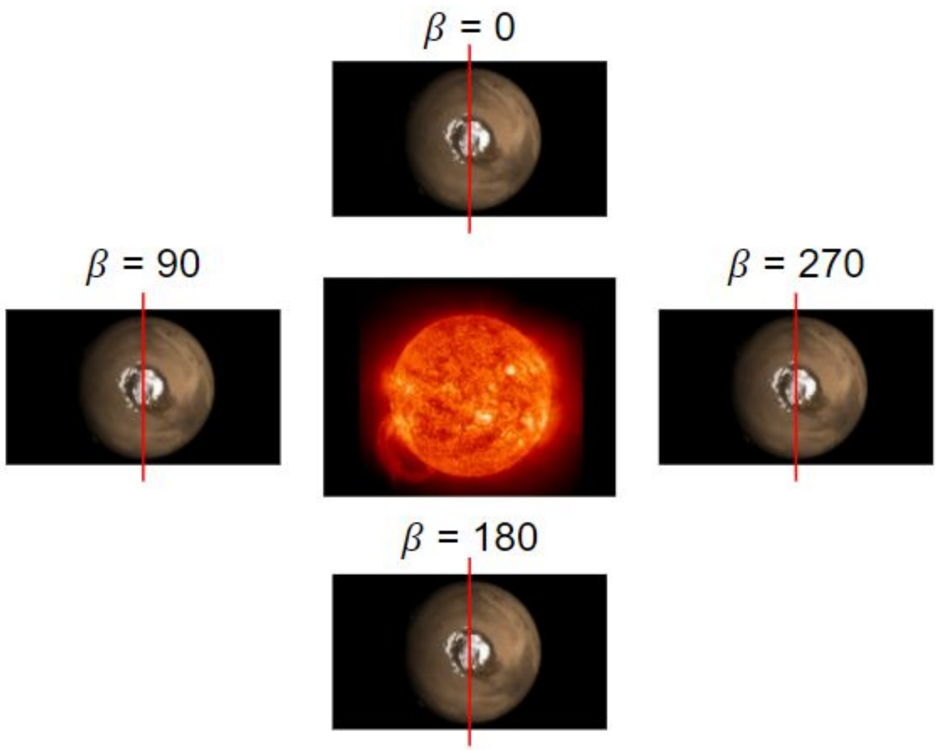
Component Selected: **[1] Clyde Space power regulator**
[2] Clyde Space battery
[3] Solar panels

Requirements	Specification	Margin
In stowed configuration, power system shall consume less than 100 W max and less than 5 W average.	1 W (hibernation mode) [1]	4W
The power system shall provide 9.5 W average power during science ops.	15 W (3.3 V) [1]	57.9%
The spacecraft shall withstand a total radiation dosage of 16060 mrad.	10 krad [1]	9900 rad
The solar array shall generate 15 Watts.	23.8 W (worst case) [3]	58.7%
The battery system shall be NiCd type battery and be able to provide a capacity of 54.2 WHr. It shall also be able to withstand 2.5 Amp current discharge	80 WHr and 8A [2]	47.6% and 5.5A
The power regulation and control system shall be 1 fault tolerant and be able to change as per designed mode requirements	1 fault tolerant [1]	0

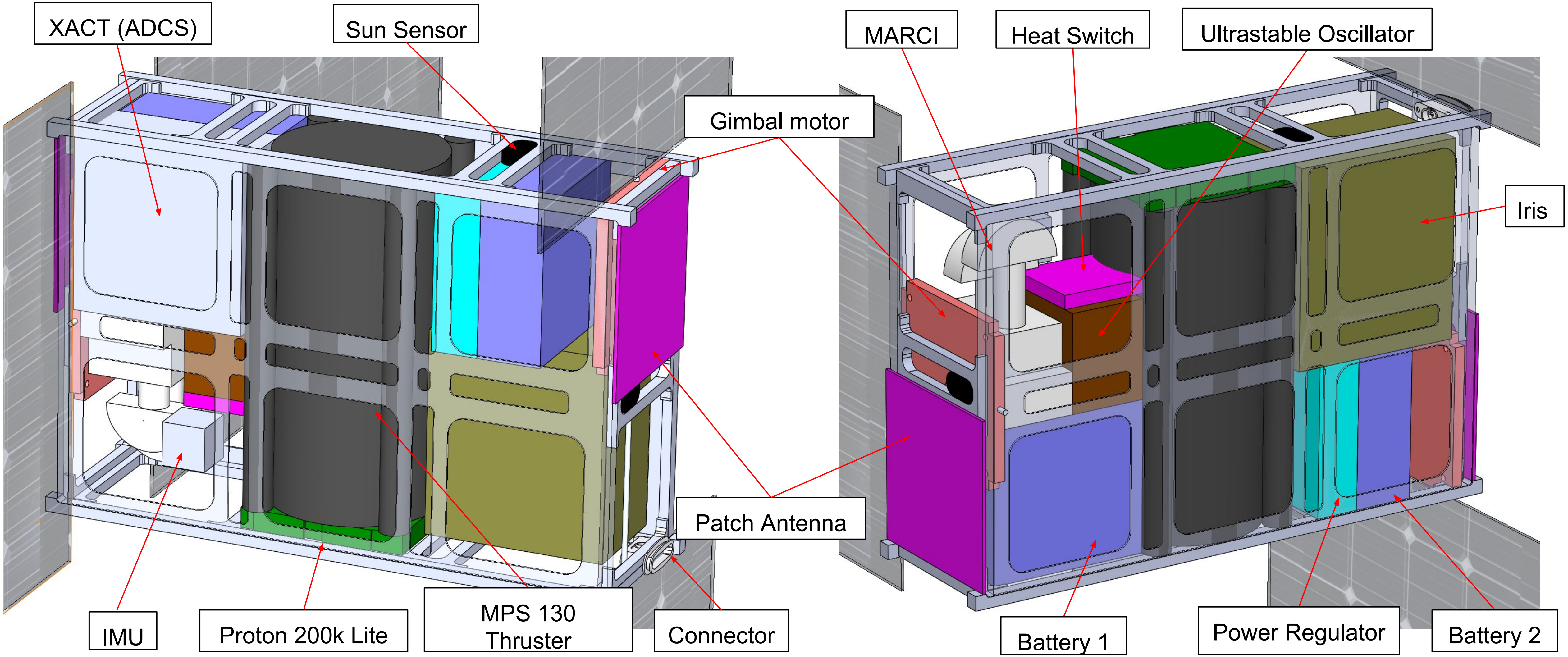
Seasonal Beta Angle Variation as a Configuration and Design Driver

Beta angle changes seasonally, causing variation in solar intensity and thus driving design to include large gimbaled solar panels to avoid instrument gimbal. Discussed in further detail in the Solar Design section.



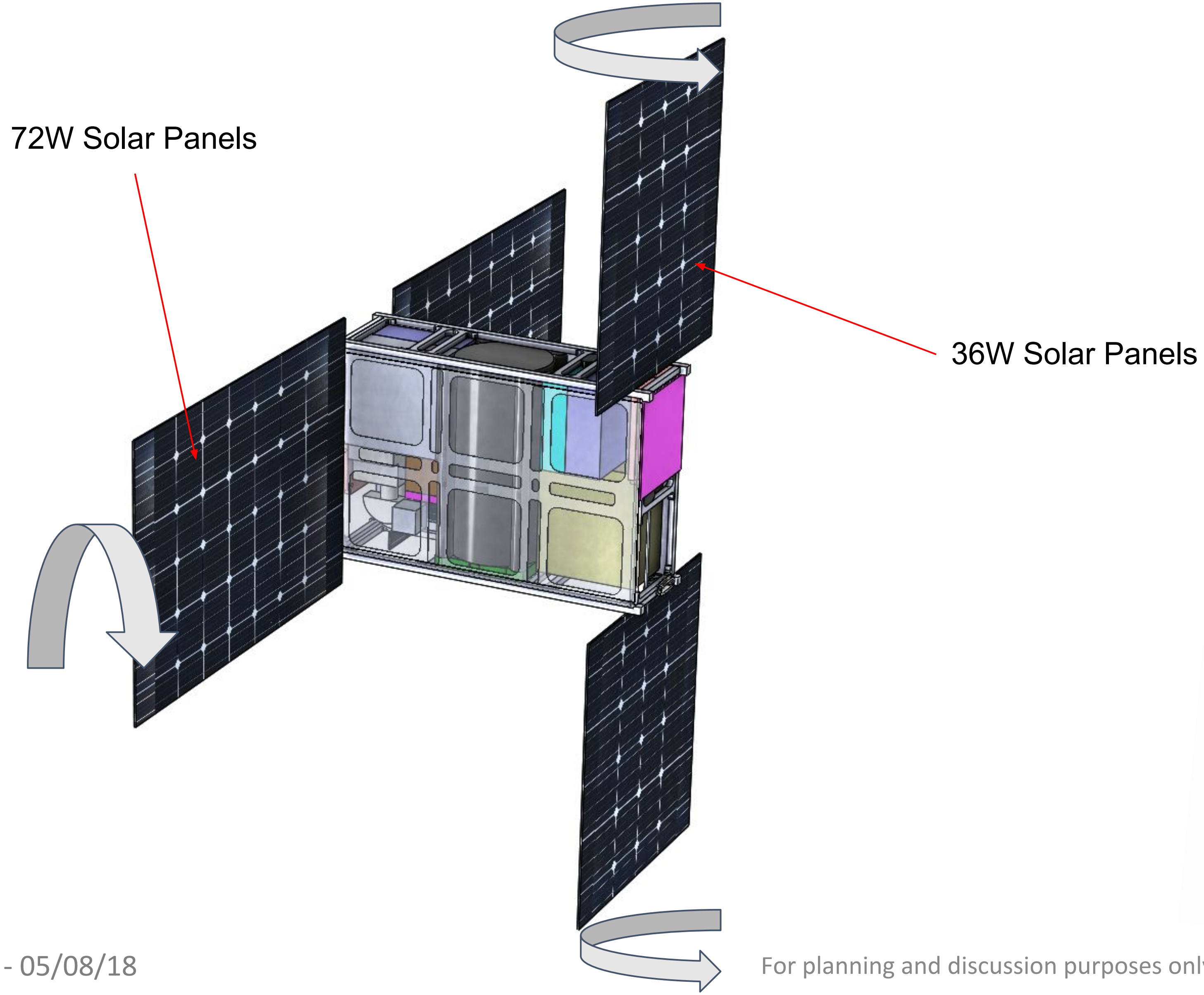


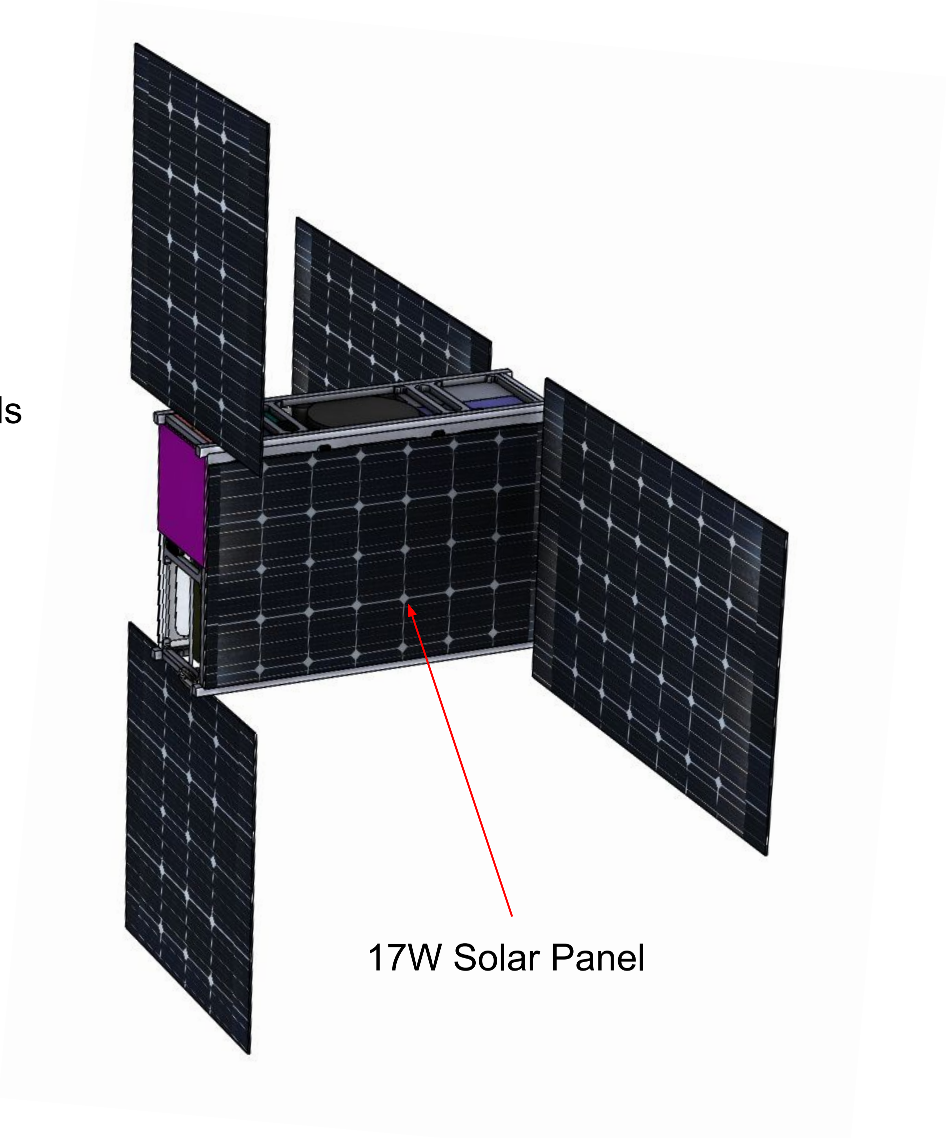
CubeSat CAD



XACT (ADCS)
Sun Sensor
Gimbal motor
MARCI
Heat Switch
Ultrastable Oscillator
Iris
Patch Antenna
IMU
Proton 200k Lite
MPS 130 Thruster
Connector
Battery 1
Power Regulator
Battery 2

CubeSat CAD Exterior





Mass Budget

System	Total mass (g)
Payload	527.00
CDH	200.00
GNC/ADCS	1,109.00
Comms/RO	1,792.00
Propulsion	2,760.00
Thermal	184.88
EPS	2,112.00
Structure	1,600.00
Total	**10,284.88**

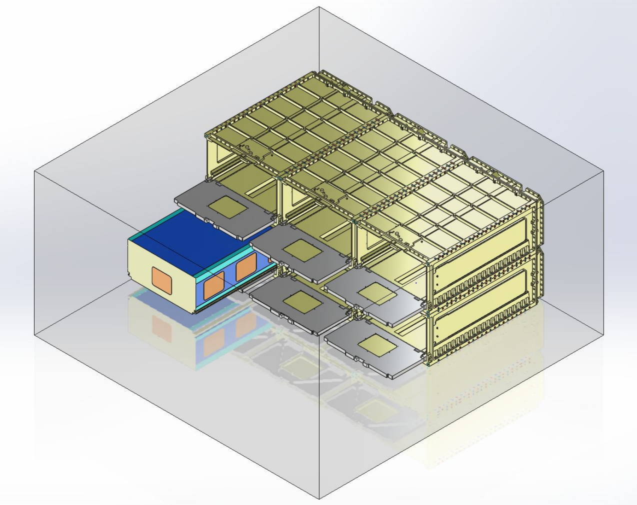
Mass Budget Notes + Secondary Payload Mass Budget

- Finding the mass requirement
  - Start from NeMO secondary payload requirement of **200 kg**
  - Baseline PPOD mass of 4.5 kg per satellite
  - Multiplying by 6 (number of satellites) and adding 5% contingency gives an estimated PPOD mass of **28.4 kg**

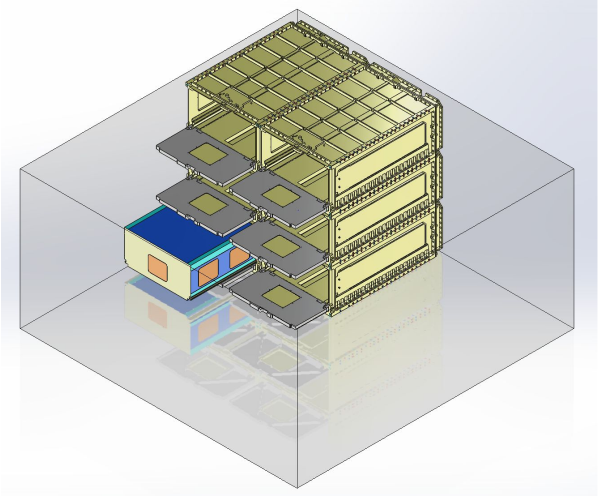
Item	Quantity	Mass (kg)
6U Cubesats	6	61.8
PPOD	6	28.4
Total		**90.2**
Max allowed		**200**
Margin		**54.9%**

CubeSat Dispensing System

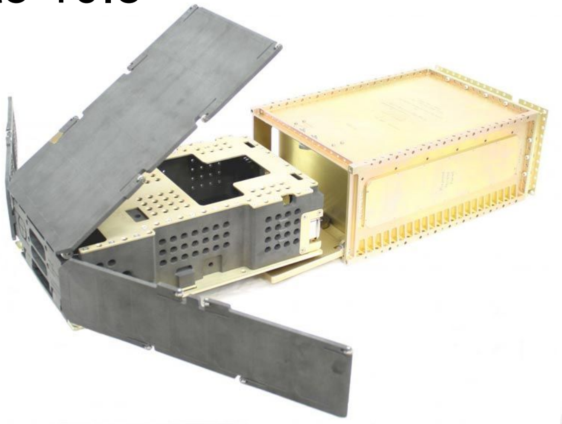
- PPOD structural Requirements:
  - Fits 6 satellites
  - Vibration requirement development: include damping material for satellites to survive worst case launch vibrations
  - NeMO secondary payload volume envelope is 1m x 1m x 0.5m
- Dispenser Specs
  - Flight Attained TRL 9 in 2013
  - Mass (x1): 4.50 kg
  - (W)×(D)×(H) = 254.63 mm × 110.3 mm × 414.3 mm
  - Payload Ejection Velocity (ΔV) [m/s]: 5.4 to 10.8
  - Survival Temperature: -39 to 85 ℃
  - Operational Temperature: -34 to 80 ℃
- Dispenser Volume Margin
  - Requirements: < 500,000 cm^3
  - Occupancy: 69,815 cm^3
  - Volume Margin: 86%



6U Horizontal Orientation



6U Vertical Orientation



Planetary Systems Corporation
Canisterized Satellite Dispenser

Questions?

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Extra Slides

NeMO Constraints

Level	Title	Constraint	Verification
L0_01	Maximum System Mass	The total system mass shall not exceed 200 kg.	Test
L0_02	Maximum System Volume	The total system volume shall not exceed 1m x 1m 0.5m.	Test
L0_03	Umbilical Power Draw	While attached to NeMO, the system shall draw less than 5 W of electrical power from NeMO.	Demonstration
L0_04	Umbilical Data Transmission Rate	While attached to NeMO, the system shall transmit less than 50 kbps of data to NeMO.	Demonstration
L0_05	Pre-Deployment Thermal Isolation	While attached to NeMO, the system shall leak less than 0.1 W of thermal energy to or from NeMO.	Test
L0_06	Deployment Operations	System deployment shall not damage or contaminate NeMO.	Analysis
L0_07	Operational Data Transmission Rate	After deployment, the system shall transmit less than 5 Gbit/day of data to NeMO for Earth relay.	Analysis
L0_08	NeMO Communications Frequency	After deployment, the system shall communicate with NeMO in the X-band or UHF bands.	Demonstration
L0_09	Multiple Spacecraft NeMO Access Limit	If the system consists of multiple spacecraft, communication with NeMO shall be limited to one spacecraft at a time.	Analysis
L0_10	NeMO Communications Data Rate	When communicating with NeMO, the communications data rate shall not exceed 10 Mbps.	Analysis

Materials Budget

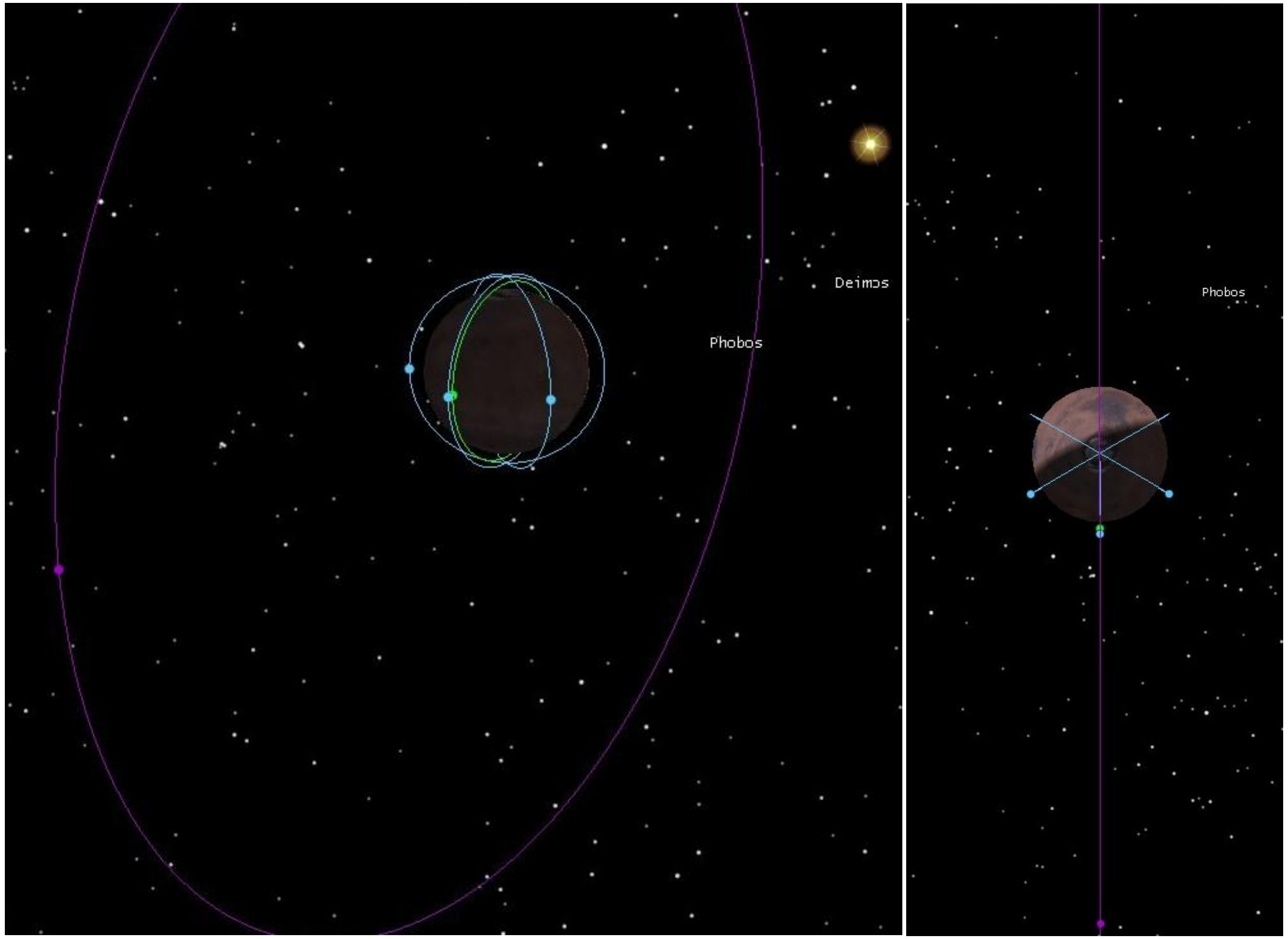
Total Materials Budget

Subsystem	Description	Model	Unit Cost (incl Contingency)	Number of Components	Total Cost	Citations
Payload	Multispectral Imager	MAEBI	$5,000,000	4	$20,000,000	Harrison, Tanya N. "Evidence For Volcanism In Martian Floor-Fractured Craters From The Mars Reconnaissance Orbiter Context Camera." 2017, doi:10.1130/abs/2017am-308639.
CDH	On-board Computer	Proton200k Lite	$15,000	6	$90,000	Harrison, Tanya N. "Evidence For Volcanism In Martian Floor-Fractured Craters From The Mars Reconnaissance Orbiter Context Camera." 2017, doi:10.1130/abs/2017am-308639.
ADC/GNC	Momentum Dumping Thruster	Boeing Palomar Micro CubeSat Propulsion System	$22,000	6	$132,000	Harrison, T. N. (2017). Evidence For Volcanism In Martian Floor-Fractured Craters From The Mars Reconnaissance Orbiter Context Camera. doi:10.1130/abs/2017am-308639 (Similar Thruster)
	Reaction Wheels	SatBus 4RW0	$17,550	6	$105,300	"CubeSat Attitude Determination & Control System (ADCS) 'SatBus CR.'" NanoAvionics, n-avionics.com/cubesat-components/attitude-control-systems/cubesat-reaction-wheels-control-system-satbus-4rw/.
	Sun Sensor	Nano-SSOC-A60	$2,574	36	$92,664	"Nano-SSOC-A60 Analog Sun Sensor." *CubeSatShop.com*, www.cubesatshop.com/product/nano-ssoc-a60-analog-sun-sensor/.
Comms/RO	Transceiver	Iris V2	$1,000,000	6	$6,000,000	*NASA*, NASA, www.jpl.nasa.gov/cubesat/missions/iris.php.
	Patch Antenna	MGA - 4x4 patch array	$2,000	18	$36,000	"Antennas." *Mouser Electronics - Electronic Components Distributor*, www.mouser.com/Passive-Components/Antennas/_/N-8w0fa.
	Ultra-Stable Oscillator (USO)	JUH/APL Disciplined USO	$230,000	6	$1,380,000	http://tycho.usno.navy.mil/ptti/2008papers/paper6.pdf
Propulsion	Thruster	Aerojet MPS-130	$88,000	6	$528,000	"MPS-130™ CubeSat High-Impulse Adaptable." *MPS-130™ CubeSat High-Impulse Adaptable | Aerojet Rocketdyne*, www.rocket.com/cubesat/mps-130.
Thermal	Heater	Kapton Insulated Flexible Heaters	$365	60	$21,900	"Flexible Heaters." *All Flex Heaters*, www.allflexheaters.com/?gclid=EAIaIQobChMIneymtvOS2gIVl4RpCh0_ZQdCEAAYASAAEgLS7fD_BwE.
	Passive Thermal Control	Thin Plate Heat Switch	$500	6	$3,000	"Heat Switch." *Bestblanks*, www.bestblanks.com/accessories.html?gclid=EAIaIQobChMI-pzdzvOS2gIViEVpCh0mVAJ7EAQYAiABEgK_6vD_BwE#2573.
EPS	Power regulator	Clyde Space: 3rd Gen EPS 01-02453	$4,400	6	$26,400	"Products." *Clyde Space*, www.clyde.space/products/19-3rd-generation-flexu-eps.
	Battery	Clyde Space: 40Whr Standalone Battery 01-02686	$3,900	12	$46,800	"Products." *Clyde Space*, www.clyde.space/products/49-40whr-cubesat-battery.
	Solar Panels	MMA eHawk	$20,000	12	$240,000	"EHaWK Solar Array." *MMA Design LLC*, mmadesignllc.com/products/ehawk-solar-array/.
Structure	Exterior Structure	ISIS 6U CubeSat Structure	$8599.5 - $9184.5	6	$55,107	"6-Unit CubeSat Structure." *ISIS - Innovative Solutions in Space*, www.isispace.nl/product/6-unit-cubesat-structure/.
Other	Star Sensor	NST-1 Nano Star Tracker	$94,820	12	$1,137,840	"NST-1 Nano Star Tracker." *CubeSatShop.com*, www.cubesatshop.com/product/nst-1-nano-star-tracker/.
Total ROM Mission Material Cost					$29,895,011	
Total ROM Mission Material Cost (30% margin)					$38,863,514	

Alternative Mission Architecture

4 CubeSats, 4 Planes

- Three 6U CubeSats
  - 600km, 90° inclination
  - 3 planes, 60° separation
  - Propulsion system
  - Multispectral Imager + Communication System
- One 3U CubeSat
  - 20,000 km, 90° inclination
  - No propulsion required
  - Communication system
- Total flight system wet mass < 50 kg (TBR)



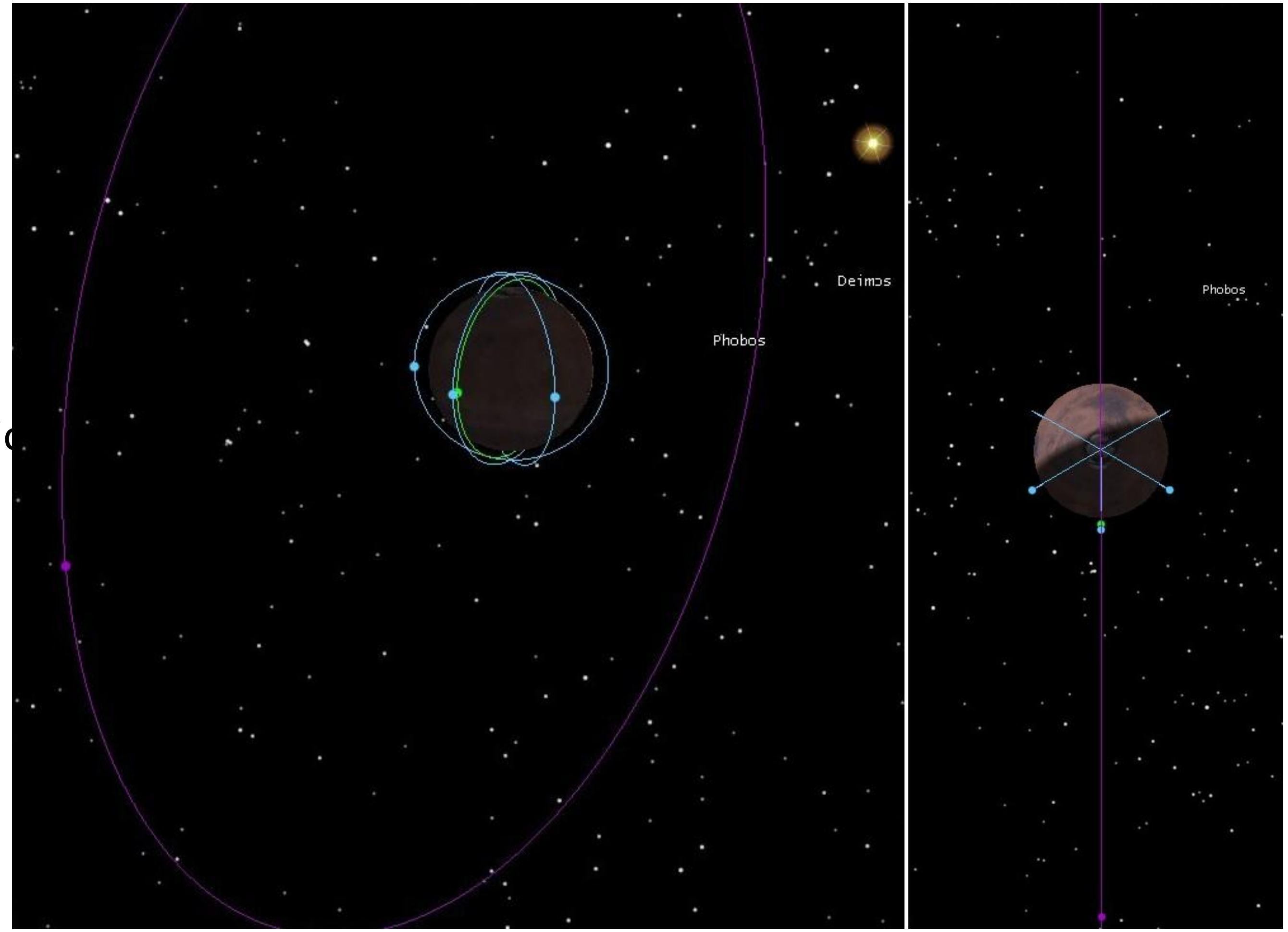
Alternative Architecture Features

Multispectral Imaging

- Global coverage
- Revisit time of ~3.5 hours
- 1.5 km/pixel resolution at Nadir
- Overlap between imager swath-widths
  - 50% orbit-to-orbit overlap
  - Stereoscopic imaging (2 hour temporal separatio

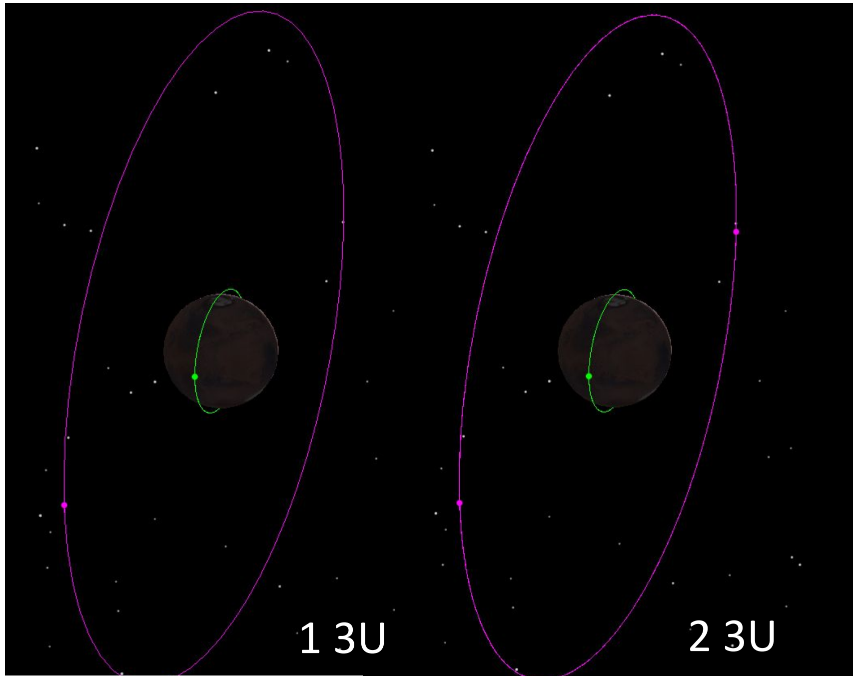
Radio Occultation

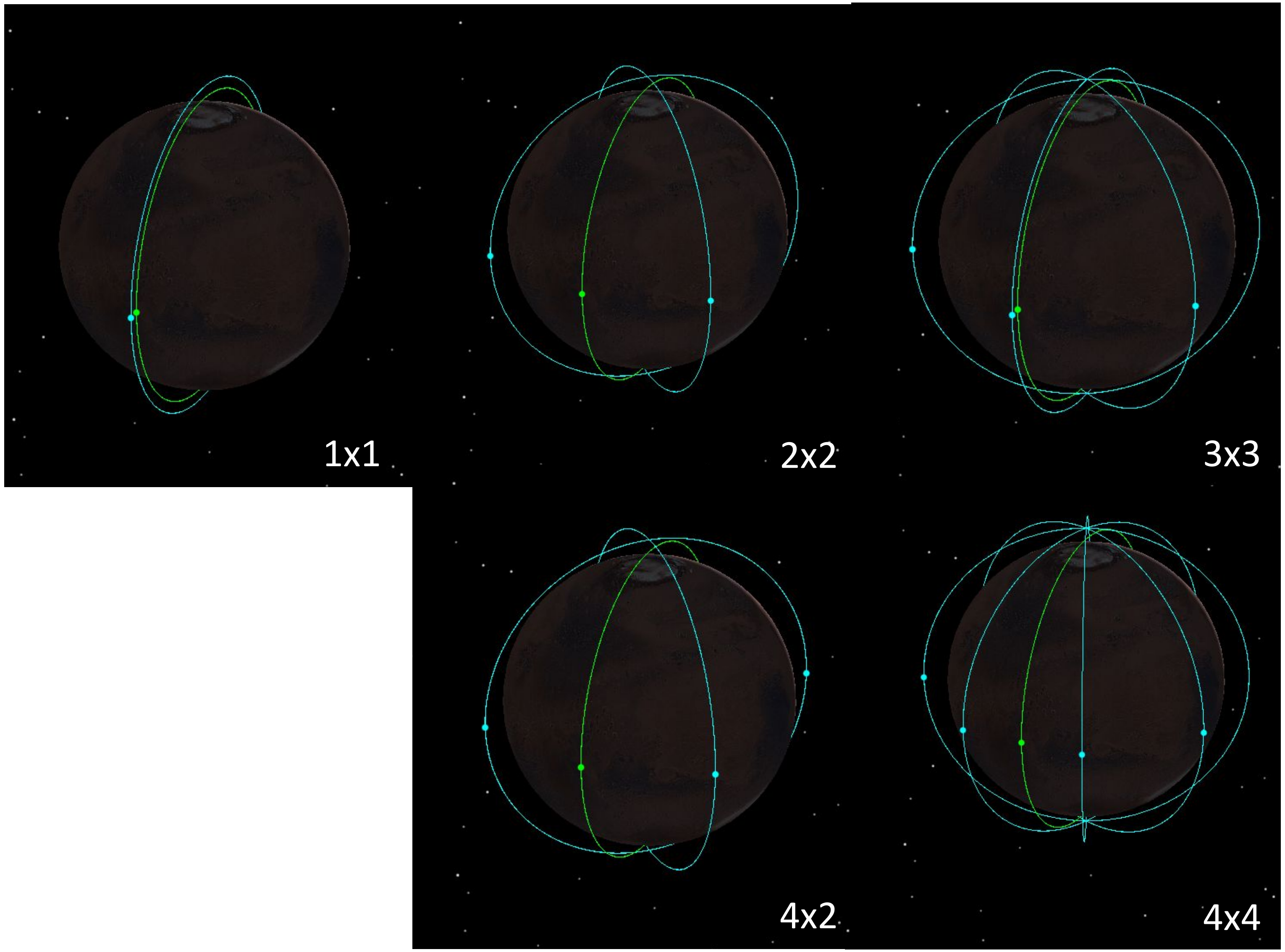
- 36 radio occultations per day



Orbital Configurations

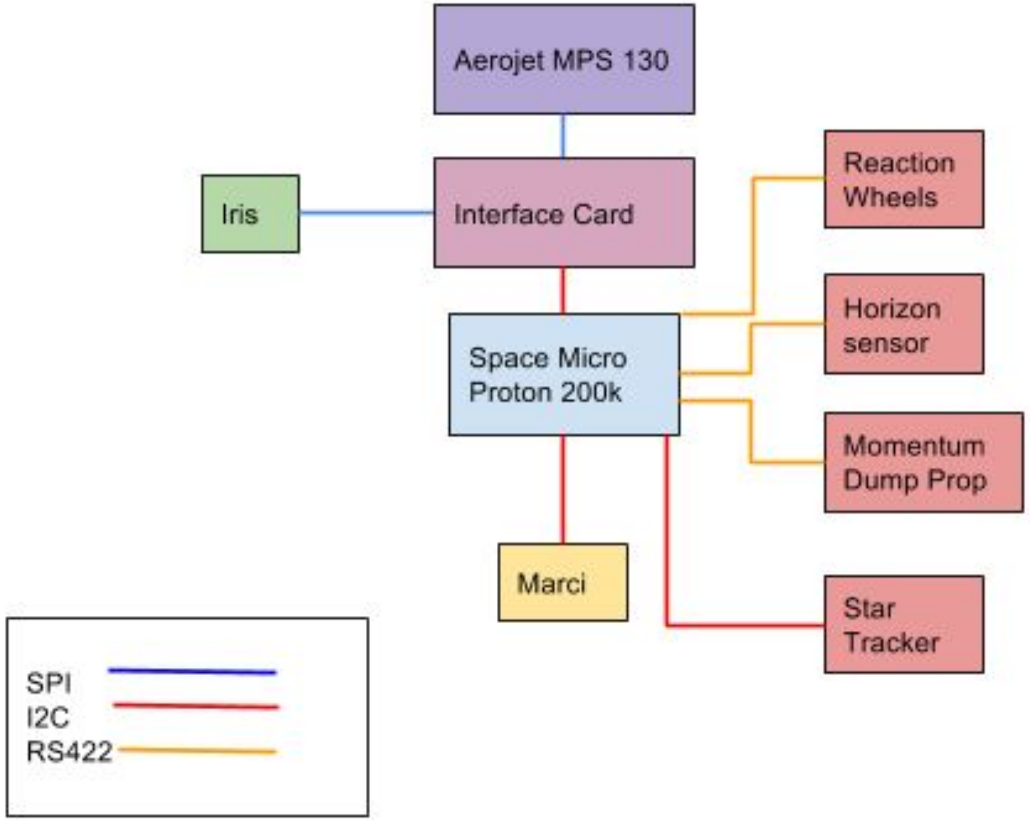
- Considerations
  - Science (revisit time)
  - Risk
  - Total mass/volume
  - Maneuver time





Command & Data Handling Interfaces

- CDH subsystem interfaces with necessary subsystems
- Interface card used with SPI interface to I2C



For planning and discussion purposes only.

ΔV Budget

B1, B4 = Inner 6Us (67.5°)

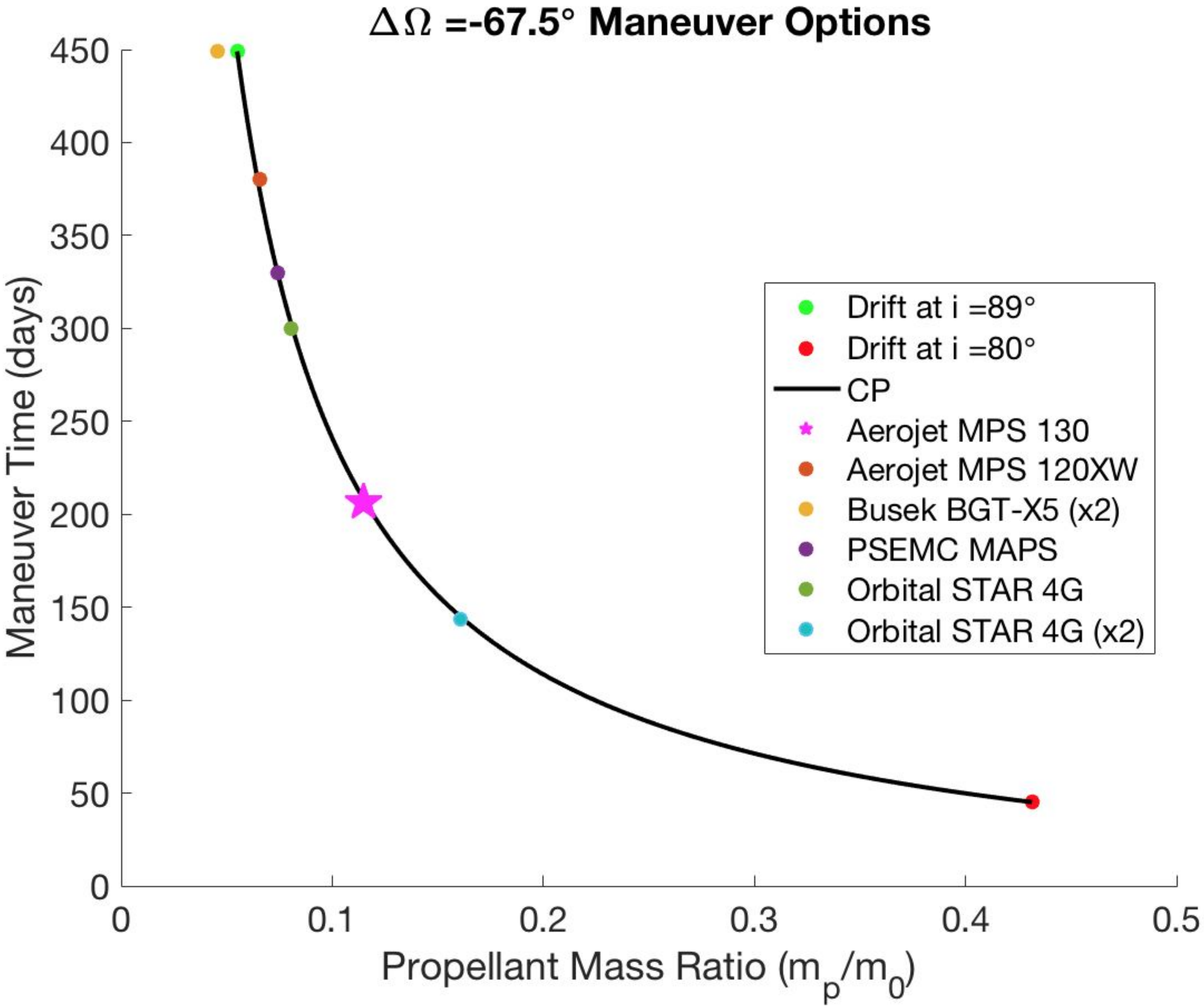
B2, B3 = Inner 6Us (22.5°)

A1, A2 = Outer 6Us

Maneuver	For CubeSats	ΔV
RAAN change (ΔΩ = ± 67.5°)	B1,B4	249 m/s
RAAN change (ΔΩ = ± 22.5°)	B2,B3	249 m/s
Propulsion Total ΔV	B1,B4	249 m/s
	B2,B3	249 m/s
Momentum Dumping	B1,B2,B3,B4	1.5 m/s
	A1,A2	0.4 m/s
Phase shift (ΔΘ = 180°)	A2	3.5 m/s
ADCS Total ΔV	B1,B2,B3,B4	1.5 m/s
	A1	0.4 m/s
	A2	3.9 m/s

Propulsion Module: Trades

- Performed trade study of commercial c
- Winner: **Aerojet Rocketdyne MPS 130 :**



Orbital Configurations

Number of Spacecraft	Constellation Configuration	Maximum Revisit Time	Maximum Individual Fuel Mass (kg)	Total Constellation Fuel Mass (kg)	Time to Baseline Science (days)	Time to Optimal Science (days)
1 (MRO + MARCI Baseline)	1 plane (90° inclination, 600 km)	11 hrs, 53 min	0	0	0	0
2	2 planes, 90° RAAN separation, 0° phase shift	5 hrs, 34 min	2.29	4.58	297.4	297.4
3	3 planes, 60° RAAN separation, 0° phase shift	3 hrs, 26 min	2.99	5.98	0	387.5
4	2 planes, 90° RAAN separation, 0° phase shift 2 spacecraft in plane, 180° phase shift	3 hrs, 46 min	2.29	9.16	297.4	297.4
4	4 planes, 45° RAAN separation, 0° phase shift	2 hrs, 7 min	3.57	9.86	154.4	463.4

Computations assume: 600 km altitude, 90° inclination, sensor HFOV = 140°, VFOV = 20°, T = 0.7 mN, Isp = 800 s, M = 9 kg, J2 perturbation, Continuous burns

Communications Trade Study

Choices / Criteria	Iris V2		Endurosat		Syrlinks		Clyde Space	
Must Haves	Info	Y/N	Info	Y/N	Info	Y/N	Info	Y/N
Required Freqency Range (X-Band)	Capable of sending and receieving in X, S, and Ka bands	Yes	Capable of only X band	Yes	Capable of only X band	Yes	Capable of only X band	Yes
Power Consumption (Must be capable of 9.22 Watts)	Up to 26 W, this has the highest out of the 4 since it supports other frequency transmissions. Comes with power supply.	Yes	Up to 15 W, comes with power supply	Yes	Up to 11 W, comes with power supply	Yes	Up to 10 W, comes with power supply	Yes
Data Rate (At least .16 Mbps)	Up to 100 Mbps	Yes	Up to 50 Mbps	Yes	Up to 100 Mbps	Yes	Up to 50 Mbps	Yes

Wants	WT	Iris V2 Info	Value	Score	Endurosat Info	Value	Score	Syrlinks Info	Value	Score	Clyde Space Info	Value	Score
Cost	1	By far the most expensive. Developed specifically for deep space missions at JPL to communicate over the DSN	1	1	Reasonably priced but is a new product.	4	4	Middle of the road in terms of price but is at TRL 9	3	3	Lowest in price but is also a new product	5	5
			1	1		4	4		3	3		5	5
			1	1		4	4		3	3		5	5
Mass	2	Most massive since it carries 3 different transmitters	1	2	0.2 kg nominal	4	8	0.225 kg nominal	3	6	.15 kg nominal	5	10
			1	2		4	8		3	6		5	10
			1	2		4	8		3	6		5	10
Lifetime (At least 3 years)	4	The only transciever I could find lifetime info on directly from brochure.	2.5	10	Lifetime has yet to be proven since it has not flown	0	0	Has flown on multiple missions	0	0	Theoretical lifetimes since it has not flown.	0	0
			3	12		0	0		0	0		0	0
			3.5	14		0	0		0	0		0	0
Flight Heritage	3	Will have TRL 9 once it launches on the MarCO Mission	1	3	No, it is still going through Qualification Testing	0	0	GOMX-3, ESA/Gomspace (October 2015), EYE-SAT, CNES (2017), OPS-SAT, ESA/TU-Graz (2017), Numerous others missions in Europe, and North America	5	15	Manufactured by ASIC, has not flown yet	0	0
			1	3		0	0		5	15		0	0
			1	3		0	0		5	15		0	0
Total Score		Minimum		16			12			24			15
		Nominal		**18**			**12**			**24**			**15**
		Maximum		20			12			24			15
		Range or Error (Max-Min)		4			0			0			0

- Iris has middle of road score
- Syrlinks has highest score by far, this has been chosen for DS9
- Mostly due to extensive flight heritage

Cost Breakdown

Instrument	Quantity	Price Each (USD)	Price Total (USD)
Payload - MARCI	4	$3,000,000	$12,000,000
Payload - CDH System	6	$4,700	$28,200
ADCS - Sun Sensors	36	$14,100	$507,600
ADCS - Reaction Wheel 1	4	$5,767	$23,068
ADCS - Reaction Wheel 2 - System	4	$17,301	$69,204
ADCS - Momentum Dumping System	6	TBR	TBR
ADCS - Horizon Sensor	6	TBR	TBR
Communications - Transceiver	6	TBR	TBR
Communications - X-Band Antenna	12	TBR	TBR
Communications - Power Amplifier	6	TBR	TBR
Propulsion - BET-1mN Thrusters	10	TBR	TBR
Propulsion - Fuel	TBR	TBR	TBR
Power - Solar Panels	TBR	TBR	TBR
Power - Batteries	TBR	TBR	TBR
Thermal - Heater	6	TBR	TBR
Thermal - Louvres	60	TBR	TBR
Thermal - MLI	6	TBR	TBR
Structures - Interior Structure	6	TBR	TBR

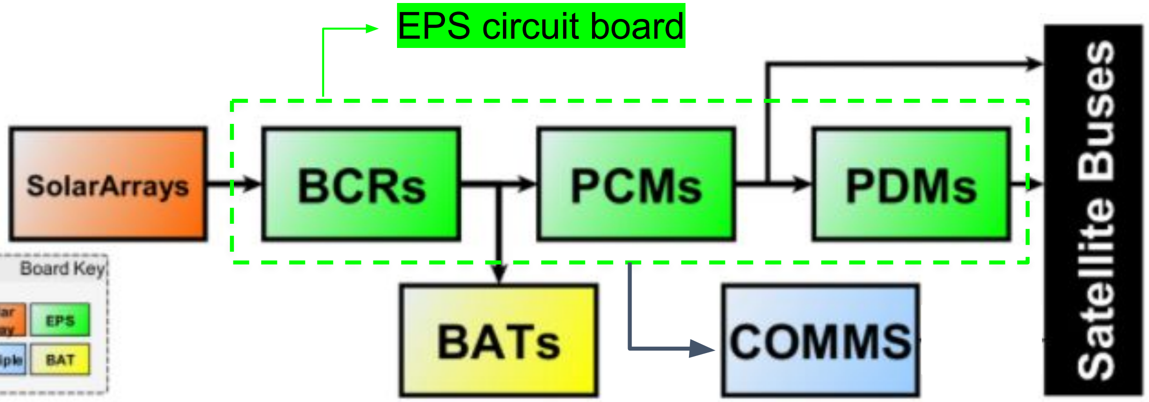
Project Risk Items

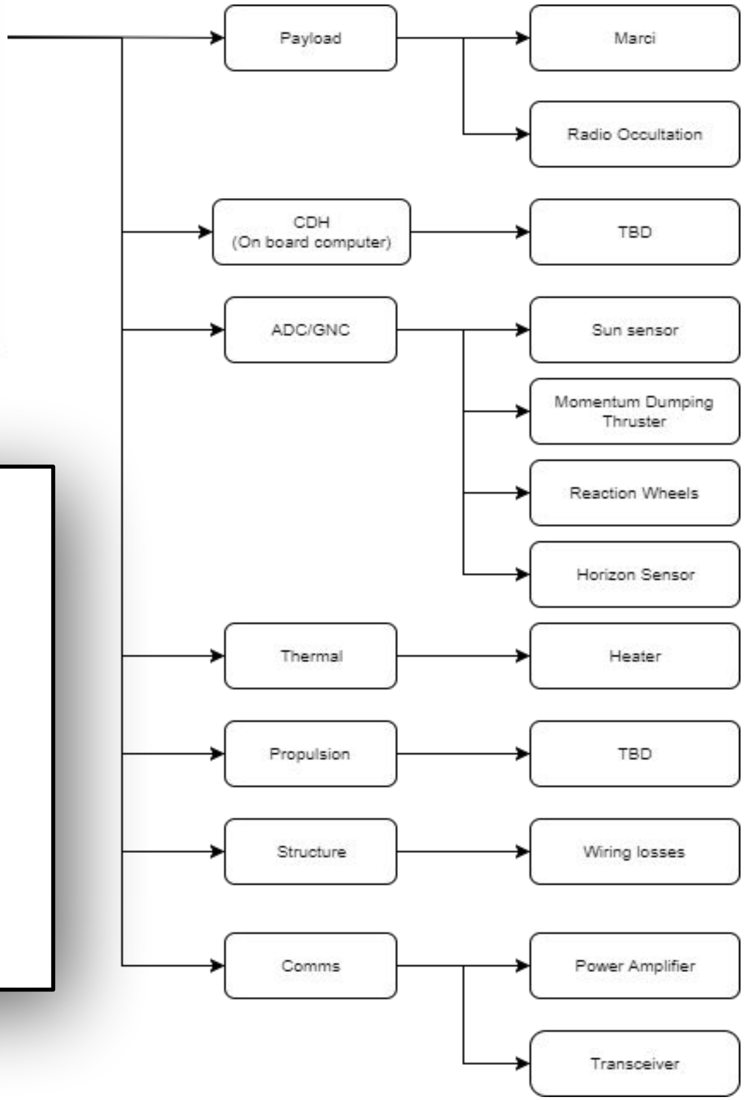
Rating	Technical Impact Justification	Schedule Impact Justification	Personnel Impact Justification
1	Lowest/least amount of overall impact	Lowest/least amount of overall impact	Lowest/least amount of overall impact
2	Slight impact on mission objectives/goals & completion	Slight impact on mission objectives/goals & completion	Slight impact on mission objectives/goals & completion
3	Large overall mission impact, certain areas directly & significantly affected	Specific mission area schedule failure, slight critical path divergence	Specific team member failure of selected tasks, slight team impact
4	Multiple areas of mission architecture directly & significantly affected	Multiple mission area schedule failure, large critical path divergence	Multiple team member failure with tasks & work completion
5	Catastrophic mission failure	Complete mission failure of schedule & divergence from critical path	Complete team structure failure & team work completion ability

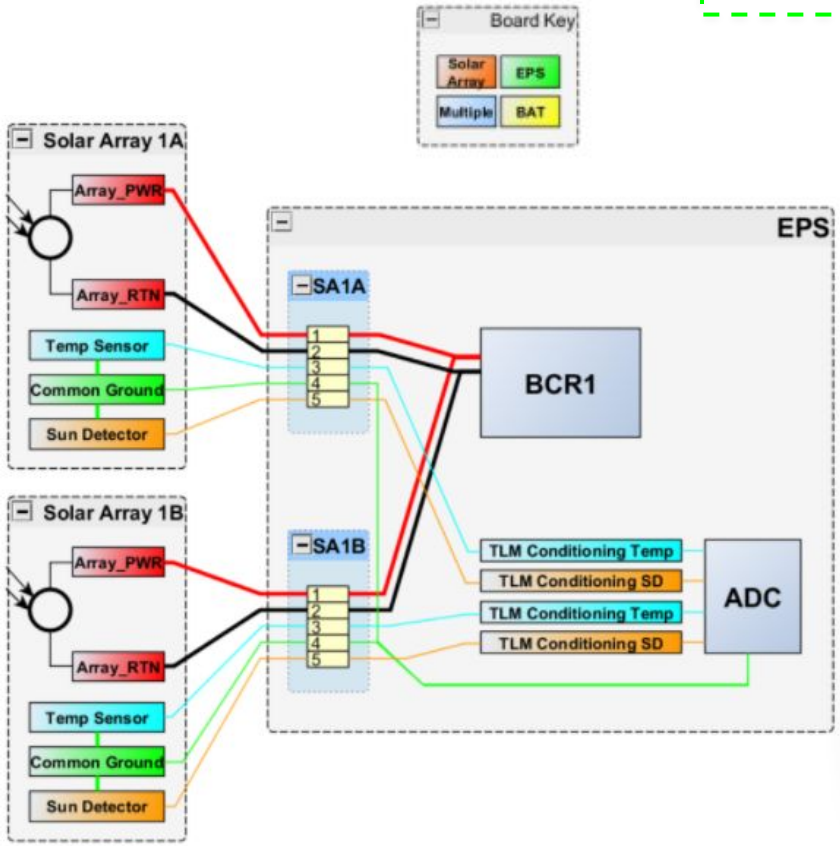
Rating	Likelihood Justification
1	Virtually NA/Remote (0-20% Chance)
2	Implausible/Unlikely (20-40% Chance)
3	Likely/Moderate Potential (40-60% Chance)
4	Highly Likely (60-80% Chance)
5	Near Definite/Assured (80-100% Chance)

Power regulation and control

Abbreviations:
- BCR : Battery charging regulator
- PCM : power conditioning module
- PDM : power distribution module
- BATs : Batteries
- COMMS : communications
- MIMO : Multi input & Multi output







Electric power regulator architecture

1) Power from solar arrays
2) BCR adjust voltage for battery charging and subsystem feeding
3) PCM monitor EPS health and report abnormal situation
4) PDM distribute power to equipment
5) MIMO feedback control for satellite attitude/ solar panel gimbal control

Project Risk Items

- Upper-level project risk items
  - Main focus: Items 1, 3, 6

Likelihood					
	5	10	15	20	25
	4	8	12	16	20
	3	6	9	12	15
	2	4	6	8	10
	1	2	3	4	5

Impact

Risk #	Risk Title	Description	Impacted Areas	Impact Score	Likelihood Score	Risk Score
1	Margins	Lack of margins available for tasks	Schedule	4	3	12
2	Imposed Requirements	Overall mission requirements fail to be met	Technical	5	2	10
3	Milestone Reviews	Failure to meet Milestone, i.e. project termination	Schedule	5	2	10
4	Technologies Available	Technologies available not satisfy needs of mission	Technical	3	3	9
5	Concept Integration	Difficulty integrating concepts for COTS into main design	Technical	3	3	9
6	Deliveries	Deliverables not completed on time or adequately	Schedule	4	2	8
7	Skills Mix	Lack of appropriate skills from team members	Personnel	3	2	6
8	Mission Operations	Failure of mission operations, i.e. constellation control, etc	Technical	4	1	4

Mission Timeline

	2022	2023	2024	2025	2026	2027	2028

	Phases and events
NeMO	Earth to Mars → Spiral In → Nominal Operations → Mission End
DS9	Hibernation → Deployment → Nominal Operations → Mission End
	Launch (7/2022)
	Deploy Outer 6U's (2/2024)
	Deploy Inner 6U's (6/2024)
	22.5° RAAN Change Achieved (Inner), 180° Phase Shift Achieved (Outer) (8/2024)
	67.5° RAAN Change Achieved (Inner) (1/2025)
	End of Life (1/2027)

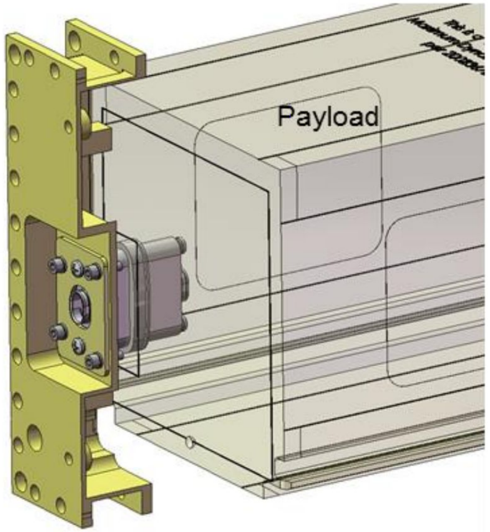
<table>
<tr><th>Phase</th><th>Hibernation</th><th>Deployment</th><th>Operations</th><th>Mission End</th></tr>
<tr><td rowspan="5">Modes</td><td rowspan="5">Hibernation</td><td>Detumble</td><td>MAEBI Data Collection</td><td rowspan="5">End of Life</td></tr>
<tr><td>Acquisition</td><td>RO Data Collection</td></tr>
<tr><td>Orbit Maneuver</td><td>Data Transfer</td></tr>
<tr><td colspan="2">Standby</td></tr>
<tr><td colspan="2">Survival (Sun Seeking)</td></tr>
</table>

CubeSat Dispensing System -Power/Comm

- **PPOD Power Supply**
  - Umbilical Power from NeMO: ≤ 100 W max, ≤ 5W average
- **PPOD Communication Supply**
  - Umbilical Power from NeMO: ≤ 100 W max, ≤ 5W average

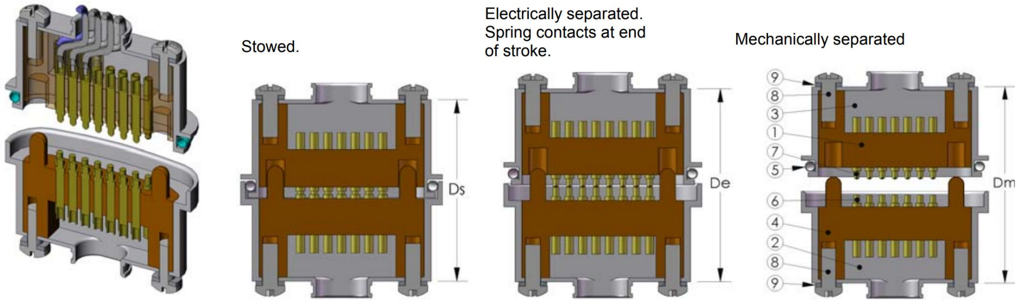
- **PPOD-CubeSat Connection**
  - 2001025 Separation Connector
  - Spring pins complete electrical junction
  - Negative insertion force
  - Spaceflight qualified/Vibration resistant
  - All power/comm are provided to CubeSat through this connector.

Connector: CubeSat side



Connector Orientation

Connector Outerview



Connector Schematic

2001025C Separation Connector Data Sheet
6U SUPERNOVATM Structure Kit Owner's Manual

Mission Elements

Ground System

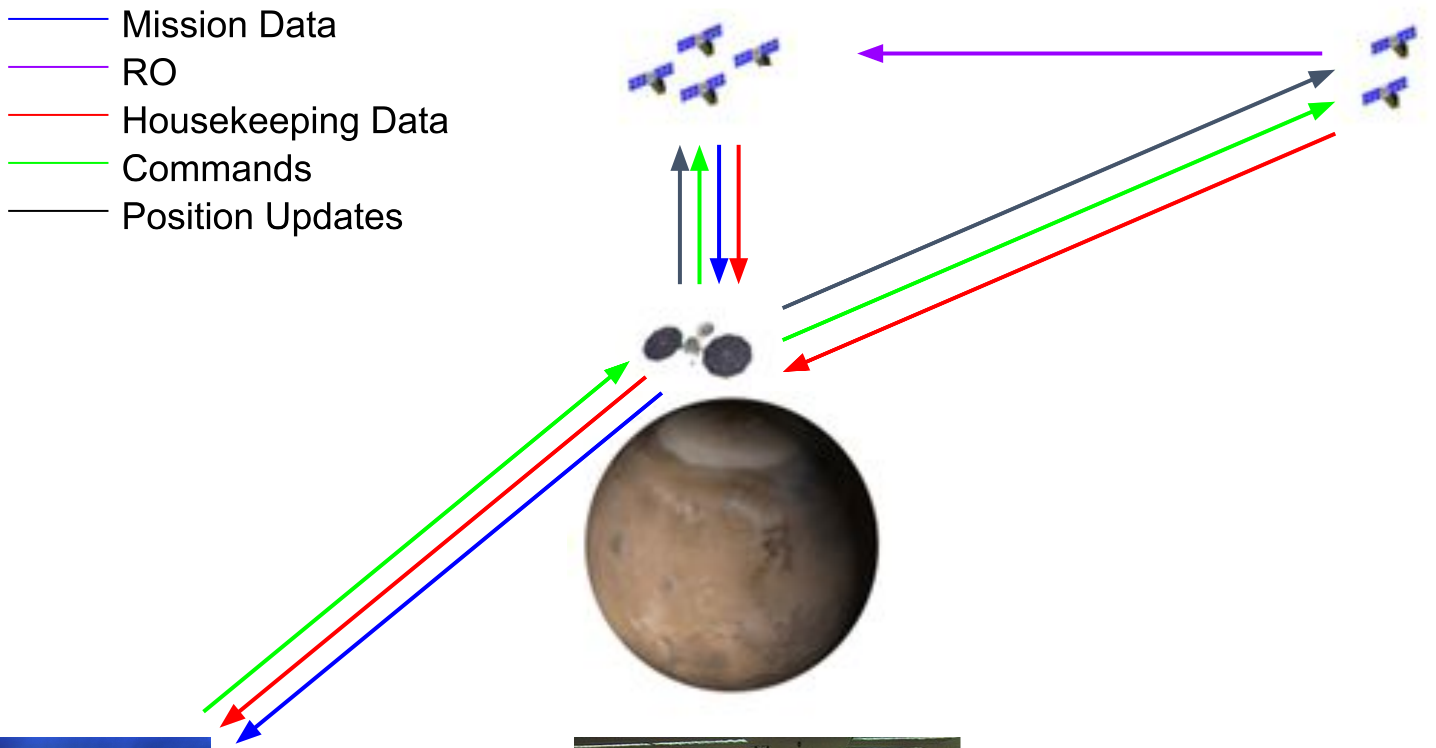
- Deep Space Network (JPL)
- Mission Control (JPL)
- Science Data Analysis Center (UM)

NeMO

- Transports Flight System to Mars
- Communications Relay to DSN

Flight System

- Stowage/Deployment Peapod
- 6U CubeSats (Imaging & Radio Occultation)



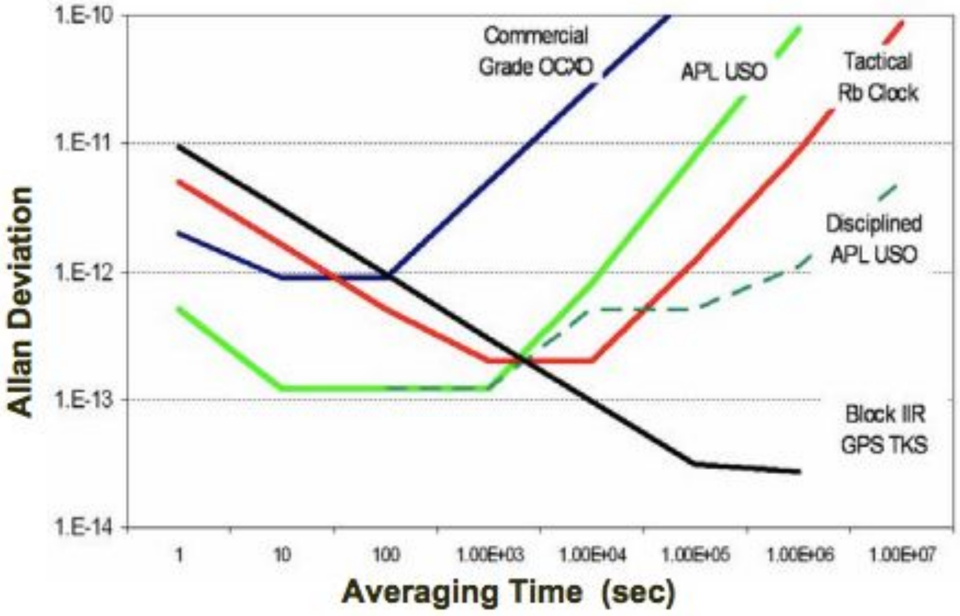
Ultra-Stable Oscillator (USO)

Deep Space 9 Subsystem Requirements					
Level	Title	Requirement	Justification	Type	Verification
L3_07	Ultra Stable Oscillator Accuracy	The Allan Deviation shall be <10^-11	Suggested by RO group at JPL. L01_06	Functional	Test

- Disciplined USO accounts for "drift correction" in frequency based on Allan Deviation characterization (Weaver et al., 2009)
- Disciplined USO shows best performance over all averaging time ranges

Parameter	MTP Design Goals	Measured performance
Output frequency and accuracy	76.364198 MHz to 76.783951 MHz (35 channels at 12.346 kHz spacing)	Maximum error to desired frequency within ± 9.8 ppm
Aging rate	$< 1 \times 10^{-10}$ per 24 hrs (spec after 30 days)	4×10^{-11} per 24 hrs (after 96 hours)
Allan deviation	$< 5 \times 10^{-13}$ at 1 s $< 2 \times 10^{-13}$ at 10 s $< 5 \times 10^{-13}$ at 100 s $< 30 \times 10^{-13}$ at 1000 s	3.6×10^{-13} at 1 s 1.6×10^{-13} at 10 s 2.9×10^{-13} at 100 s 10.2×10^{-13} at 1000 s
Single sideband phase noise	< -95 dBc/Hz at 1 Hz < -110 dBc/Hz at 10 Hz < -120 dBc/Hz at 100 Hz < -125 dBc/Hz at 1 KHz	-95 dBc/Hz at 1 Hz -107 dBc/Hz at 10 Hz -117 dBc/Hz at 100 Hz -122 dBc/Hz at 1 KHz
Frequency vs. temp.	$< 1 \times 10^{-12}$ per degree C	7×10^{-13} per degree C
Frequency vs. load	$< 2 \times 10^{-12}$ over 45 to 55 Ohms	4×10^{-13} over 45 to 55 Ohms
Frequency vs. voltage	$< 1 \times 10^{-12}$ over 22 to 35 Volts	$< 4 \times 10^{-12}$ over 22 to 35 Volts
Input DC power at 28 V spacecraft buss	< 0.8 W steady-state in vacuum	< 1.1 W steady-state in vacuum < 2.2 W operating in air 4.4 W warm up at 35 V
Mass	< 550 grams	480 grams
Performance and operating temperature	+20 to +40 C (performance) +15 to +45 C (proto-flight) -25 to +65 C (operating survival)	+15 to +45 C (verified performance over proto-flight) -25 to +65 C (operating survival)

(Weaver et al. 2009)



(Lewin et al., 2007)

Link Budget - Devised method

- Heritage from Grail Mission - Lunar Gravity Ranging System
- Assemblies - Gravity Processor Recovery Assembly (S band)
  Microwave Assembly (Ka Band)
  - Additional Power requirements
- X- Band - Patch Antenna 9.2W
  Ka-Band - Parabolic Antenna 0.5W
  S-Band - Horn Antenna 2W
- High complexity in mounting/gimbaling three different Antennas
- High Precision Values not a part of requirement.
- Mass/ Volume Constraints

Item	Symbol	Units	Source	X-Band Patch	Ka-Band Parabolic	S-Band Horn
Frequency	f	GHz	Input Parameter	8.2	32	2
Transmitter Power (DC)	P	Watts	Input Parameter	9.22	0.5	0.2
Transmitter Power Amplifier Efficiency	hp	--	Input Parameter	0.08	0.08	0.03
Transmitter Power (RF)	P	Watts	P*hp	0.74	0.04	0.01
Transmitter Power (RF)	P	dBW	10 log(P)	-1.32	-13.98	-22.22
Transmitter Line Loss	Ll	dB	Input Parameter	-2	-1	-1
Transmit Antenna Beamwidth	θt	deg	Input Parameter	65	5	35
Transmit Antenna Efficiency	ht	--	Input Parameter	0.5	0.9	0.9
Peak Transmit Antenna Gain	Gpt	dBi	Eq. (13-18b)	16	31.22	40
Transmit Antenna Diameter	Dt	m	Input Parameter	0	0.5	0.3
Transmit Antenna Pointing Error	et	deg	Input Parameter	6.5	0.5	3.5
Transmit Antenna Pointing Loss	Lpt	dB	Eq. (13-21)	-0.12	-0.12	-0.12
Transmit Antenna Gain (net)	Gt	dBi	Gpt+ Lpt	15.88	31.1	39.88
Equiv. Isotropic Radiated Power	EIRP	dBW	P + Ll+ Gt	12.56	16.12	16.66
Propagation Path Length	S	km	Input Parameter	2.70E+04	2.70E+04	2.70E+04
Space Loss	Ls	dB	Eq. (13-23a)	-199.34	-211.17	-187.09
Propagation & Polarization Loss	La	dB	Fig. 13-10	0.1	0	0
Receive Antenna Diameter	Dr	m	Input Parameter	0	0.5	0.3
Receive Antenna Efficiency	hr	--	Input Parameter	0.5	0.9	0.9
Peak Receive Antenna Gain	Grp	dBi	Eq. (13-18b)	16	31.22	40
Receive Antenna Beamwidth	θr	deg	Eq. (13-19)	65	5	35
Receive Antenna Pointing Error	er	deg	Input Parameter	6.5	0.5	3.5
Receive Antenna Pointing Loss	Lpr	dB	Eq. (13-21)	-0.12	-0.12	-0.12
Receive Antenna Gain (net)	Gr	dBi	Grp+ Lpr	15.88	31.1	39.88
System Noise Temperature	Ts	K	Table 13-10 or DSN table	25	25	25
Data Rate	R	bps	Input Parameter	1000	5400	10000000
Modulation Rate	--	--	Input Parameter	0.5	0.5	0.5
Computer Implementation Efficiency	--	--	Input Parameter	0.9	0.9	0.9
Effective Data Rate	R	bps	*See cell	2222	12000	22222222
Eb/No(1)	Eb/No	dB	Eq. (13-13)	10.3	9.85	10.58
Carrier-to-Noise Density Ratio	C/No	dB-Hz	Eq. (13-15a)	43.77	50.65	84.05
Bit Error Rate	BER	--	Input Parameter	1.00E-07	1.00E-07	1.00E-07
Required Eb/No(2)	Req Eb/No	dB	Fig. 13-9	5.8	5.8	5.8
Implementation Loss (3)	---	dB	Input Parameter	-1.5	-1	-1
Rain Attenuation (4)	--	dB	Fig. 13-11	0	0	0
Margin	---	dB	(1) – (2) + (3) + (4)	**3**	**3.05**	**3.78**

Link Budget - Revised Method

Single X-Band Configuration						
Item	Symbol	Units	Source	Inner 6U to NeMO	Outer 6U to Inner 6U	Outer 6U to Inner 6U (Housekeeping)
Frequency	f	GHz	Input Parameter	8.20	8.20	8.20
Transmitter Power (DC)	P	Watts	Input Parameter	6.80	1.42	8.23
Transmitter Power Amplifier Efficiency	hp	--	Input Parameter	0.15	0.08	0.08
Transmitter Power (RF)	P	Watts	P*hp	1.02	0.11	0.66
Transmitter Power (RF)	P	dBW	10 log(P)	0.09	-9.45	-1.82
Transmitter Line Loss	Ll	dB	Input Parameter	-1.00	-2.00	-2.00
Transmit Antenna Beamwidth	θt	deg	Input Parameter	70.00	70.00	70.00
Transmit Antenna Efficiency	ht	--	Input Parameter	0.50	0.50	0.50
Peak Transmit Antenna Gain	Gpt	dBi	Eq. (13-18b)	16.00	16.00	16.00
Transmit Antenna Diameter	Dt	m	Input Parameter	0.01	0.01	0.01
Transmit Antenna Pointing Error	et	deg	Input Parameter	7.00	7.00	7.00
Transmit Antenna Pointing Loss	Lpt	dB	Eq. (13-21)	-0.12	-0.12	-0.12
Transmit Antenna Gain (net)	Gt	dBi	Gpt+ Lpt	15.88	15.88	15.88
Equiv. Isotropic Radiated Power	EIRP	dBW	P + Ll+ Gt	14.97	4.43	12.06
Propagation Path Length	S	km	Input Parameter	2500.00	27000.00	27000.00
Space Loss	Ls	dB	Eq. (13-23a)	-178.67	-199.34	-199.34
Propagation & Polarization Loss	La	dB	Fig. 13-10	0.05	-0.03	0.05
Receive Antenna Diameter	Dr	m	Input Parameter	0.30	0.01	0.01
Receive Antenna Efficiency	hr	--	Input Parameter	0.90	0.50	0.50
Peak Receive Antenna Gain	Grp	dBi	Eq. (13-18b)	27.77	16.00	16.00
Receive Antenna Beamwidth	θr	deg	Eq. (13-19)	8.54	70.00	70.00
Receive Antenna Pointing Error	er	deg	Input Parameter	0.10	7.00	7.00
Receive Antenna Pointing Loss	Lpr	dB	Eq. (13-21)	0.00	-0.12	-0.12
Receive Antenna Gain (net)	Gr	dBi	Grp+ Lpr	27.77	15.88	15.88
System Noise Temperature	Ts	K	Table 13-10 or DSN table	70.00	25.00	25.00
Data Rate	R	bps	Input Parameter	1250000.00	150.00	1000.00
Modulation Rate	--	--	Input Parameter	0.50	0.50	0.50
Computer Implementation Efficiency	--	--	Input Parameter	0.90	0.90	0.90
Effective Data Rate	R	bps	*See cell	2777777.78	333.33	2222.22
Eb/No(1)	Eb/No	dB	Eq. (13-13)	9.83	10.33	9.81
Carrier-to-Noise Density Ratio	C/No	dB-Hz	Eq. (13-15a)	74.26	35.56	43.27
Bit Error Rate	BER	--	Input Parameter	0.00	0.00	0.00
Required Eb/No(2)	Req Eb/No	dB	Fig. 13-9	5.80	5.80	5.80
Implementation Loss (3)	---	dB	Input Parameter	-1.00	-1.50	-1.00
Rain Attenuation (4)	--	dB	Fig. 13-11	0.00	0.00	0.00
Margin	---	dB	(1) – (2) + (3) + (4)	3.03	3.03	3.01

Configuration	Symbol	Units	3 Band Configuration	Single Band Configuration
Total Power Consumption	P	Watts	9.22	6.8

Project Risk Mitigation

Risk #	Risk Title	Risk Level	Corresponding Date	Mitigation Strategy	Changes
1	Margins	12	3/18/17	-	-
		6	3/18/17	Impact & Likelihood Risk reduction – Allocate time for each subsystem's work more effectively, giving more "free" time for when needed	Impact from 4 to 3, Likelihood from 3 to 2
2	Imposed Requirements	10	3/18/17	-	-
		5	3/24/17	Likelihood Risk reduction – Clarify requirements from Stakeholders on regular basis for any updates/changes & act accordingly	Likelihood from 2 to 1
3	Milestone Reviews	10	3/18/17	-	-
		5	3/18/17	Likelihood Risk reduction – Plays into margins & motivation, ensure completion of work for Milestones with time for team review before deadline	Likelihood from 2 to 1
4	Technologies Available	9	3/18/17	-	-
		6	3/31/17	Likelihood Risk reduction – Thoroughly research COTS products available before determining critical limiting factors of systems	Likelihood from 3 to 2
5	Concept Integration	9	3/18/17	-	-
		6	3/31/17	Likelihood Risk reduction – Develop thorough initial structure with defined area allocations for subsystems to use as COTS parameters	Likelihood from 3 to 2
6	Deliveries	8	3/18/17	-	-
		4	3/18/17	Likelihood Risk reduction – Like Milestone reviews, ensure adequate scheduling & time for completion with team review before deadlines	Likelihood from 2 to 1

GNC Future Work

- Selection of IMU
  - Derivation of RO position and velocity requirements
  - Determine effects of ADCS operations on IMU requirements
  - Determine suitable IMU with specifications to meet these requirements
- Thorough pointing budget
- ACS Thruster analysis to determine appropriate duty cycling and propellant mass
- Determine control scheme and model in Simulink
- Downsize COTS hardware if possible