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Mars Telecommunications CubeSat Constellation Relay

April 26th, 2016

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Mars Telecom Investigation Team

Motivation/ Background

Overview

Flight System

Telecom Relay Performance

Summary

David Spencer, Aerospace Engineering
Space systems, mission design

Rohan Deshmukh, Aerospace Engineering
Packaging, system engineering

Swapnil Pujari, Aerospace Engineering,
Telecommunications, data volumes

Giovanny Guecha, Aerospace Engineering,
Subsystem trade studies

The Mars Telecom Investigation Team would like to acknowledge and thank the following people for their input and support during this study:

JPL: Tom Komarek, Robert Lock, Chad Edwards, Ryan Woolley, Sara Spangelo, Courtney Duncan

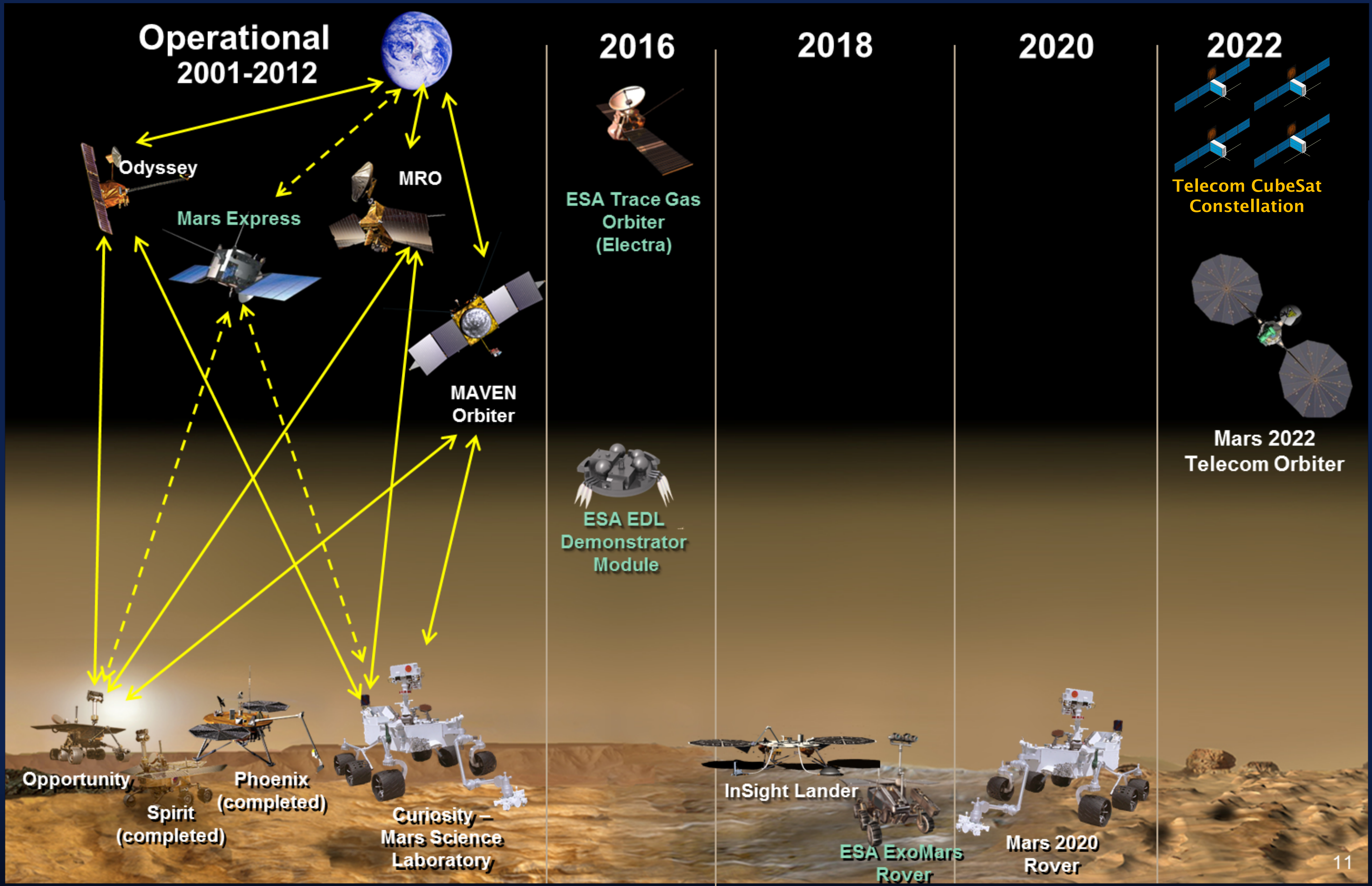
Georgia Tech: Glenn Lightsey, Adam Snow, Sean Chait, Terry Stevenson

Concept Overview

- A constellation of four 6U CubeSats in high inclination Mars orbit augments telecom relay capability for landed assets
  - Benefits include increased frequency of command (forward link) opportunities, and increased return data volumes from surface assets
  - Constellation utilizes both DTE/DFE relay as well as UHF cross-link relay with existing telecommunication orbiters
- Concept is targeted for 2022 launch opportunity, deployed from 2022 Mars Orbiter
  - 4-CubeSat constellation established with 350 km circular altitude, high inclination orbit, with evenly phased RAAN
  - Study team also evaluated constellation performance in an equatorial orbit
    - Two aerocapture delivery systems deployed during Mars approach capture into equatorial Mars orbit; each aerocapture system deploys two CubeSats into low-Mars orbit.
    - CubeSats deployed from launch vehicle upper stage at launch, use ion propulsion for interplanetary transfer and orbit capture. This approach was found to be infeasible with current CubeSat-class ion propulsion systems.

Mars Mission Architecture

- Motivation/ Background
- Overview
- Flight System
- Telecom Relay Performance
- Summary



Credit: Chad Edwards – Jet Propulsion Lab

Telecom Relay Architecture

Motivation/ Background
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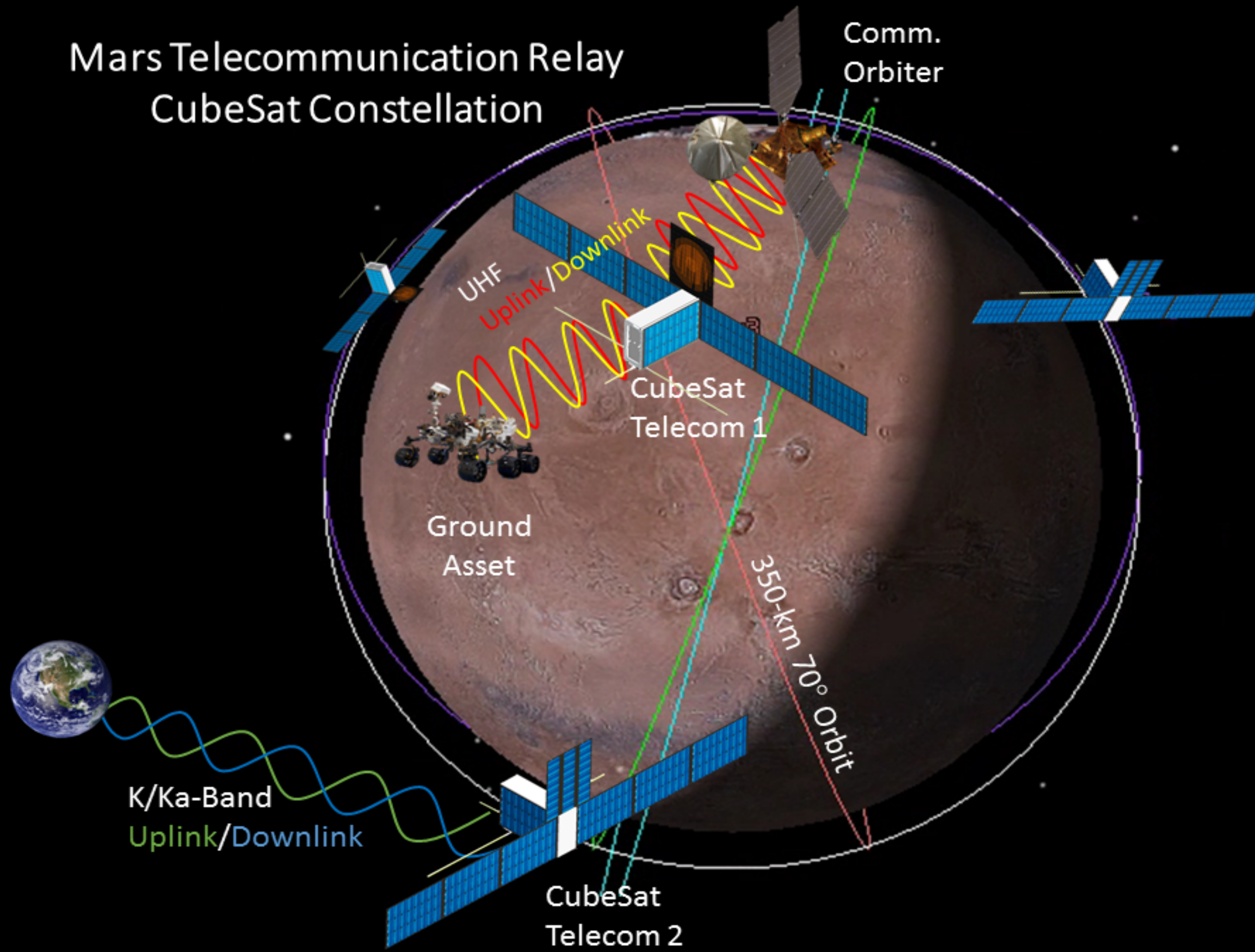
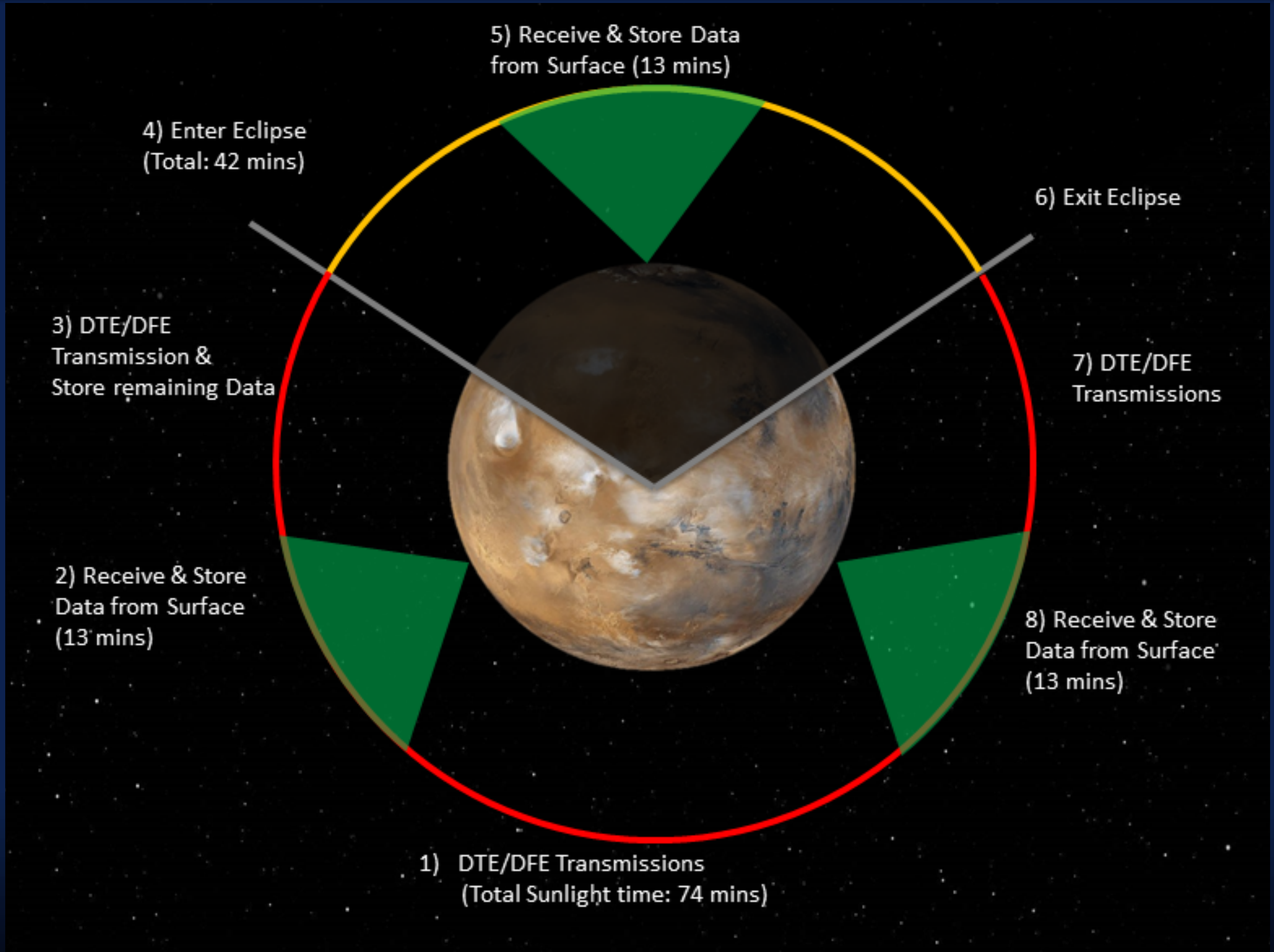


Orbit Timeline & Data Return Strategy



Total Orbital Period: 116 minutes = 1.93 hr

Flight System Deployed Configuration

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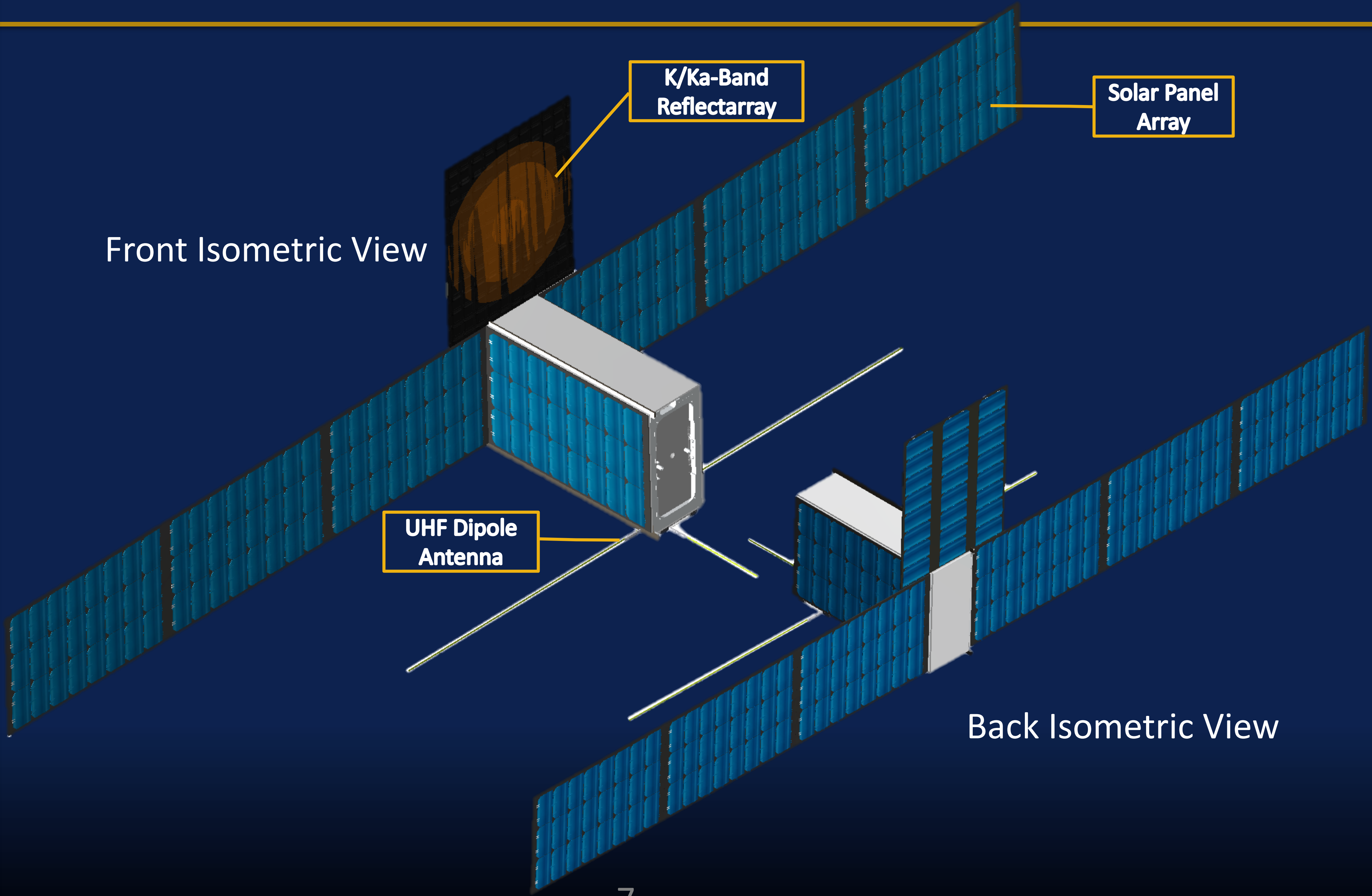

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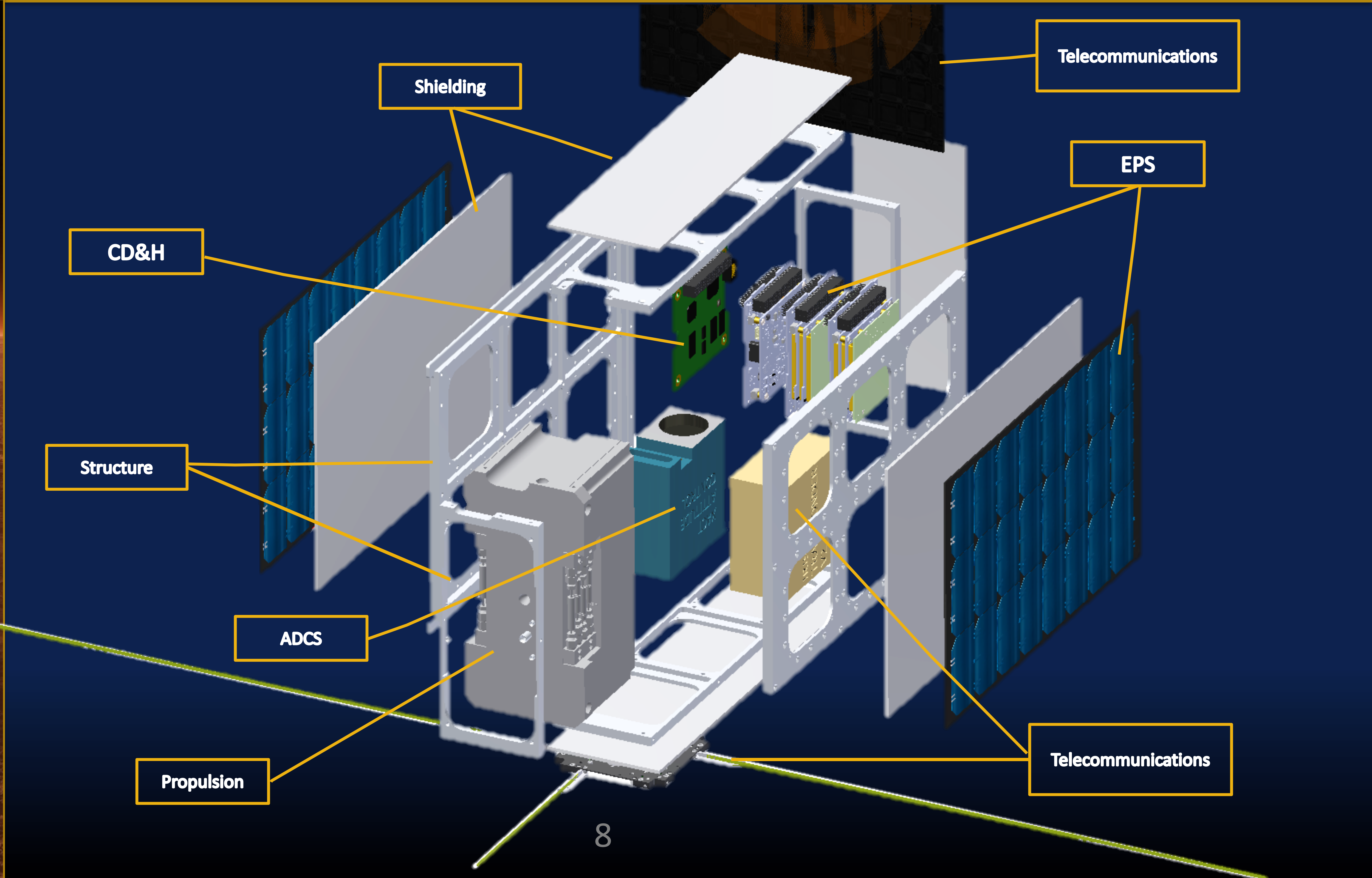
Flight System Exploded View



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Master Equipment List

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Subsystem	Component Name	Quantity	CBE Mass (g)	Contingency	MEV Mass (g)
ADCS	BCT-XACT Module	1	850	5%	893
Telecom	IRIS v2 Transponder	1	1200	15%	1380
	UHF Monopole Antenna (ISIS)	1	100	5%	105
	Ka-Band Reflectarray	1	500	15%	575
Propulsion	Cold Gas Thruster (dry)	1	1500	15%	1725
Structures	6U CubeSat Structure	1	1640	5%	1722
	Aluminum Shielding	1	990	5%	1039
C&DH	Proton 200k Lite Processor	1	200	5%	210
EPS	Clyde Space FLEX EPS	1	173	5%	182
	CS 30 W-hr Battery	2	260	5%	546
	CS Deployable 6U Panels	6	290	15%	2001
	CS 6U Body Mounted Solar Panels	2	290	15%	667
Thermal	Heaters	2	10	10%	22
	MLI	1	200	5%	210
				MEV Dry Mass	11,276
				Propellant Mass	920
				MEV Wet Mass	**12,196**
				Mass Margin	1,803 (15%)
				MPV Mass	14,000

Telecom Analysis Assumptions

- DTE downlink data volume calculations based on Earth-to-Mars range (1 AU)
- Transmit DTE/DFE when not in eclipse
  - Transmit 1.23 hours per orbit
- 8 hours DSN (34 m BWG) pass per sol, 3 times per week
  - Multiple Spacecraft Per Antenna (MSPA) capability
  - Up to four simultaneous downlinks
- UHF crosslink to MAVEN/TGO/MTO based upon orbit geometries, data rates consistent with average range

Communications Opportunities

- 4-CubeSat constellation provides 15 overflights per sol with respect to an equatorial surface asset
  - 2022 orbiter offers four overflights per sol
  - MAVEN offers two overflights per sol
- 70° inclination orbit with RAAN of 0°, 90°, 180°, 270° enables no greater than ~ 3.5 hours communications “blackout” periods
  - Constrained due to constellation orbit geometry

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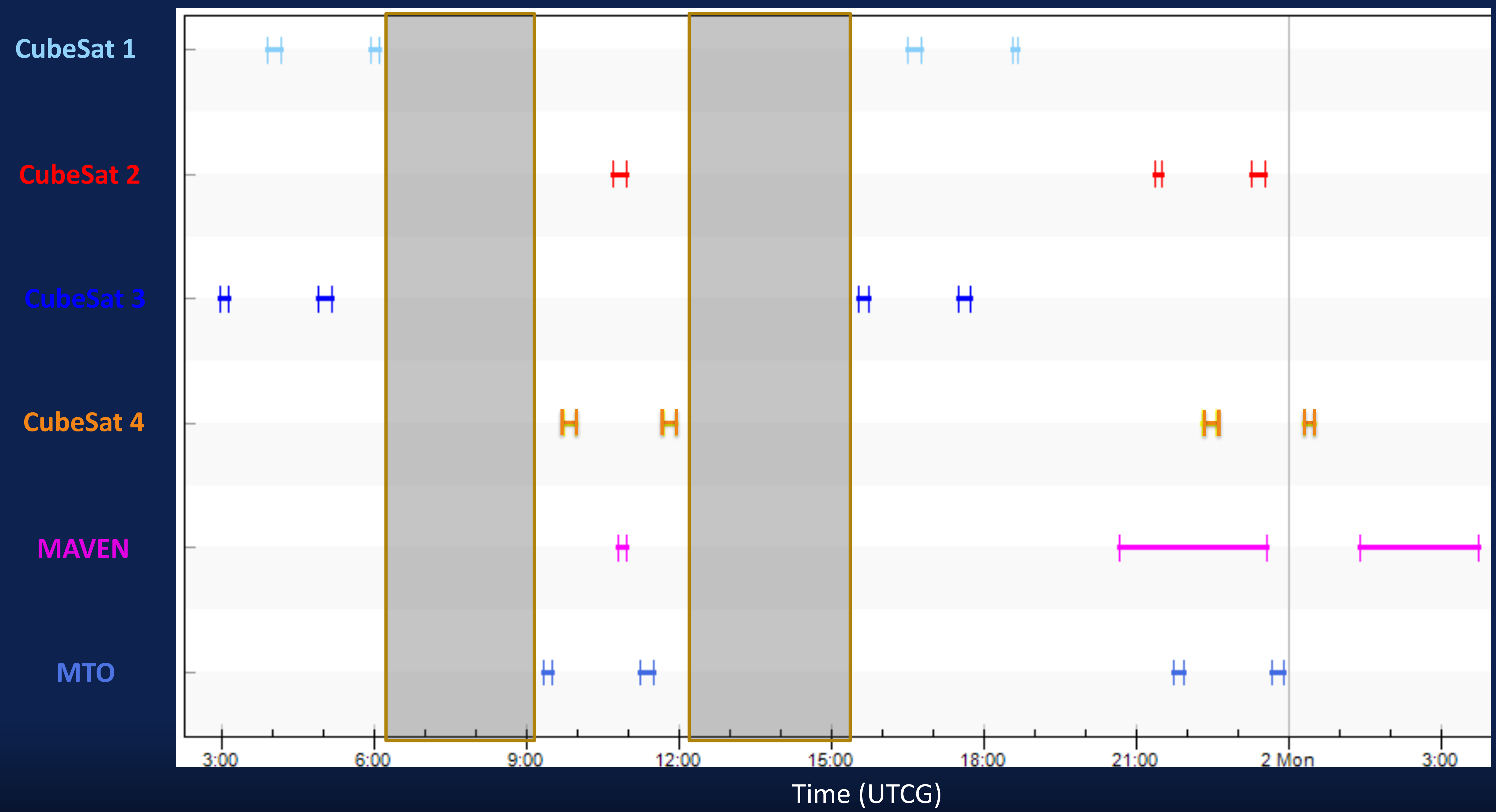
Equatorial Surface Asset Coverage Plot



4-CubeSat Constellation Return Link Capability

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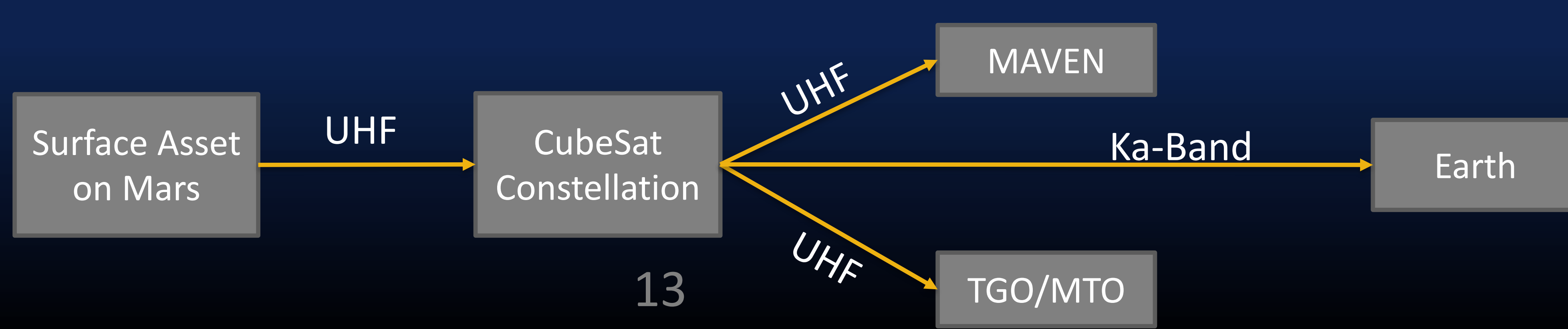
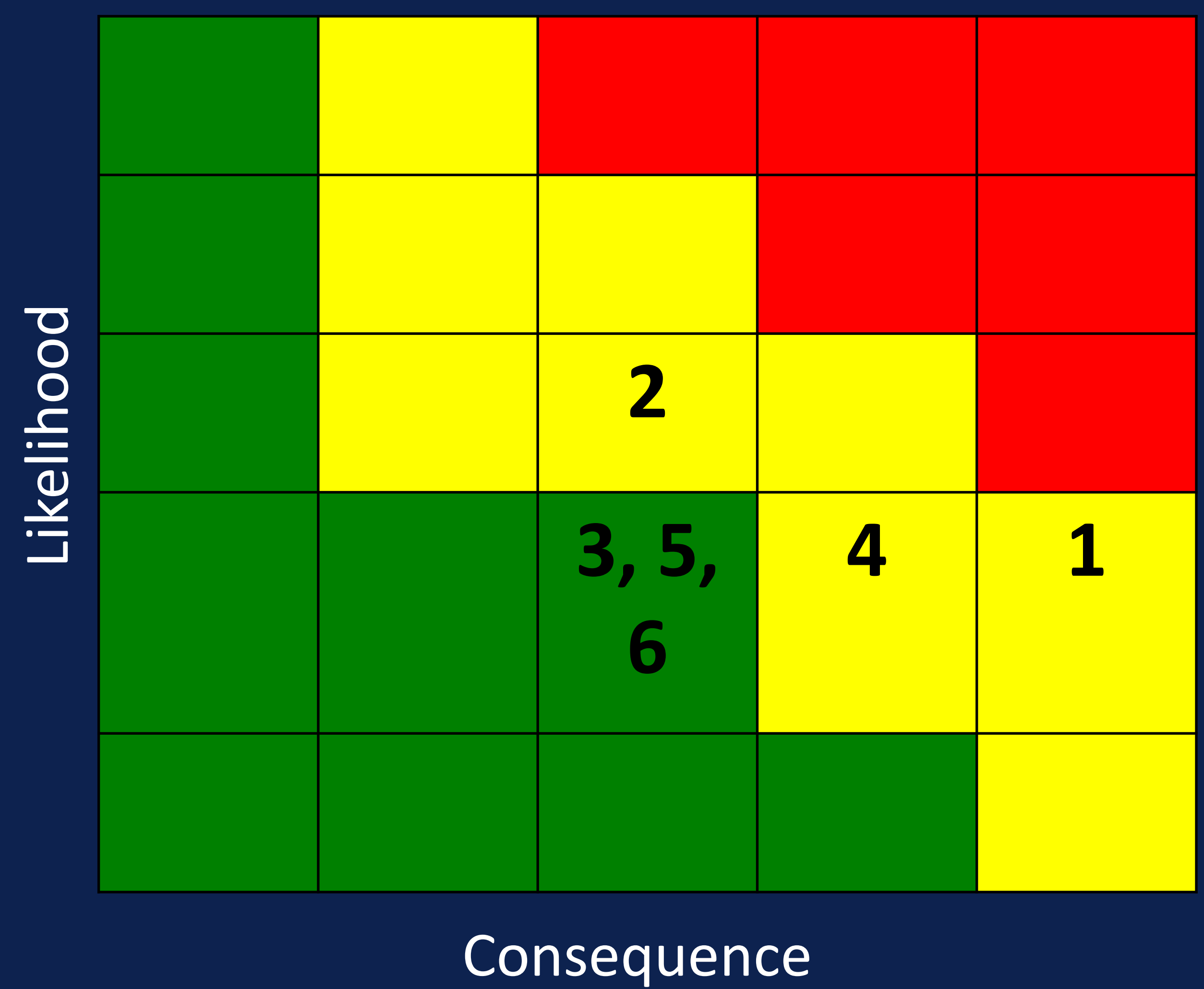
CubeSat Constell. Inclination (deg)	Surface Asset Latitude (deg N)	CubeSat Constell. Avg # of Passes/Sol	CubeSat Avg. Pass Duration (min)	Surface to CubeSat Constell. Avg. Data Volume (Mb/Sol)	CubeSat Constell. Avg. Data Volume Per Sol via MAVEN (Mb/Sol)	CubeSat Constell. Avg. Data Volume Per Sol via TGO/MTO (Mb/Sol)	CubeSat Constell. Avg. Data Volume Per Sol DTE (Mb/Sol)
70	0	14.3	13.0	547	45	589	342
70	10	14.6	13.0	556	45	589	342
70	20	15.5	13.1	589	45	589	342
0	0	45.7	17.5	3647	64	298	342
0	10	45.7	16.1	2373	64	298	342
0	20	45.7	10.8	914	64	298	342



Technical Risks

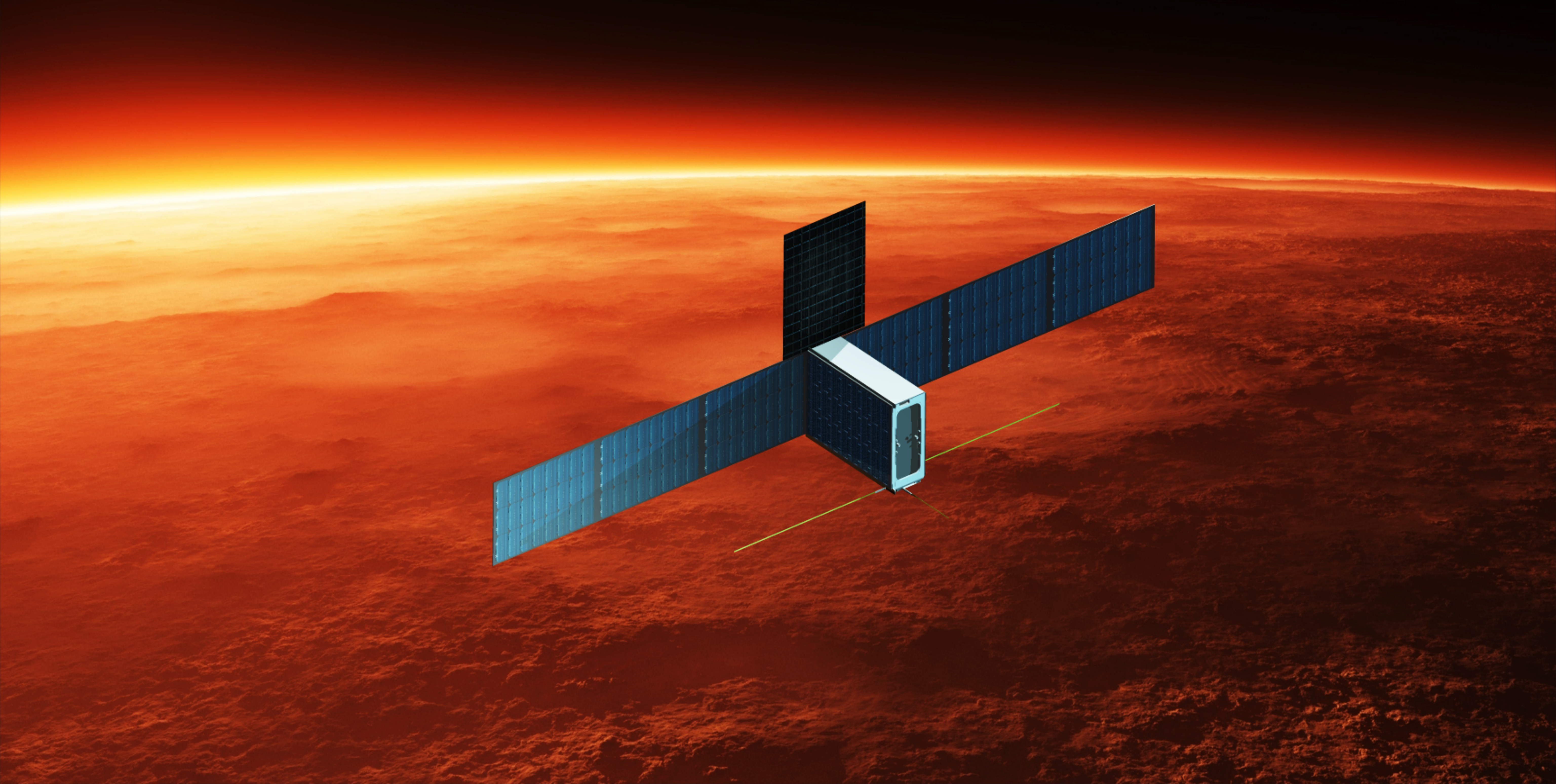


1 – Solar panel deployment
2 – Radiation tolerance
3 – DTE Pointing accuracy
4 – Propulsion system performance
5 – Ka-band reflect array deployment
6 – UHF antenna deployment

Conclusions

- CubeSat constellation provides a dramatic increase in the frequency of communications opportunities with landed assets
  - Frequent uplink opportunities would be a major benefit to operations teams scheduling the building and transmission of command products
  - Allows > 500 Mb/sol surface-to-cubesat data volume
  - No greater than 3.5 hour communications "blackout" periods with equatorial surface assets
- Allows an average of 342 Mb/sol DTE capability
- Technical resource budgets show that 6U CubeSat design is feasible for Mars telecommunications relay application

Questions?



Backup Slides

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Key Driving Requirements

- The telecommunications relay constellation shall consist of four 6U CubeSats.
  - 36 cm x 24 cm x 12 cm 6U form factor, maximum CubeSat mass 14 kg.
- The CubeSats shall be deployed from MTO into low-Mars orbit, and shall maneuver into the constellation configuration.
- The constellation orbit shall have a 350 km altitude, with an inclination equal to that of the 2022 Mars Telecom Orbiter (MTO).
- The CubeSats shall be phased 90 deg apart along the orbit.
- The constellation shall provide direct-from-Earth (DFE) forward link and direct-to-Earth (DTE) return link relay for near-equatorial surface assets.
- The constellation shall provide UHF forward- and return-link relay between surface assets and MAVEN/TGO/MTO.
- The CubeSats shall be capable of operating for two Mars years in the Mars environment.

Telecommunications

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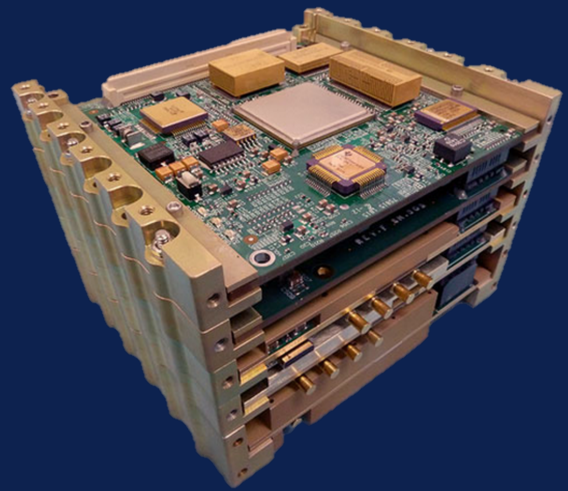
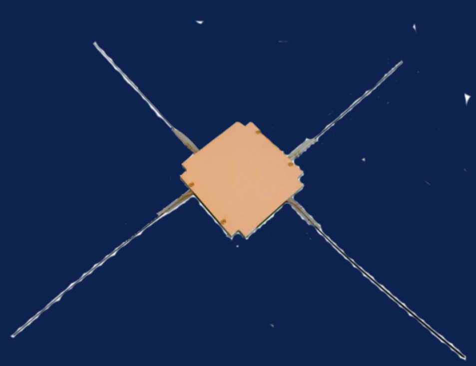
Subsystem	Component Name	Quantity
Telecom	IRIS Transponder v2	1
	K/Ka-Band Reflectarray	1
	UHF 4 Monopole Antenna (ISIS)	1

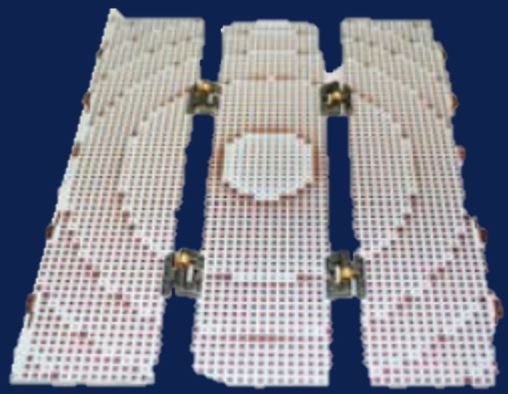


IRIS Transponder v2 (NASA JPL):

- Currently: X-Band (Rx/Tx)
- Capabilities: UHF, Ka (both Rx/Tx)
- Max 5W RF Output Power
- Radiation Tolerant
- BPSK Modulation



UHF 4-Way Monopole Antenna



K/Ka-Band Reflectarray Antenna[1]

Telecommunications Characteristics	Value
Patched Area	33 x 27 x 0.24 cm
Antenna Gain	33.5 dBi
Frequency[2]	32 GHz
Stowed Area	30 x 10 x 0.72 cm

1. Antenna characteristics are based off existing ISARA Reflectarray Antenna
2. Frequency modified to meet DSN specifications/ IRIS v2 capabilities

Sources: *CubeSat Antenna Datasheet, NASA*
IRIS V2 CubeSat Deep Space Transponder, NASA

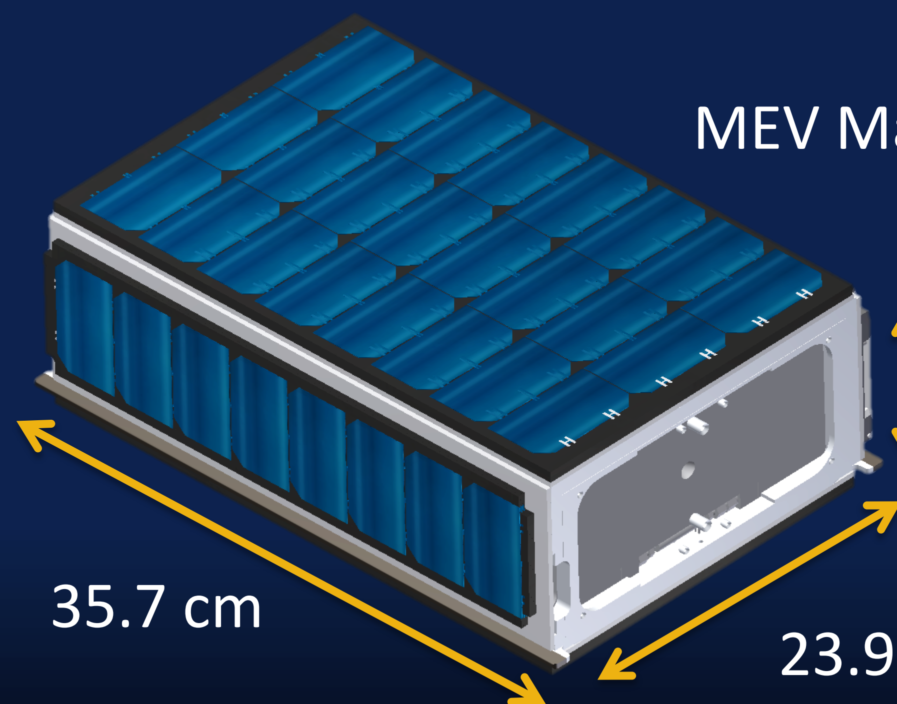
Structure

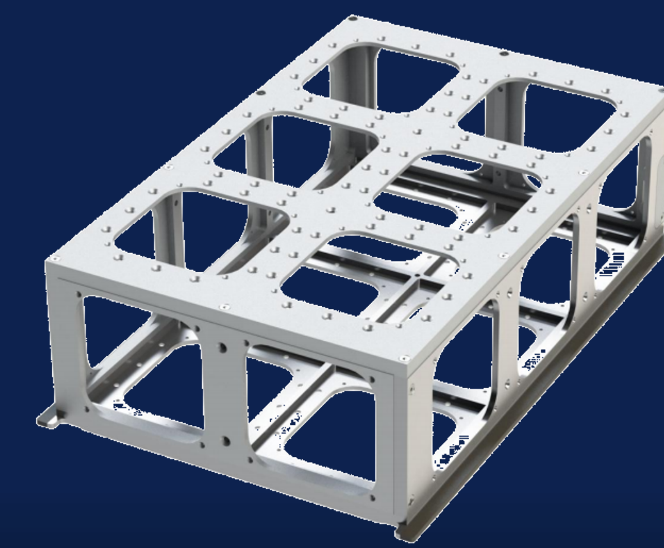
Pumpkin Supernova 6U aluminum structure provides mounting locations for all subsystem components

- 6U CubeSat structure complies with CubeSat deployer standards
  - 12 cm x 24 cm x 36 cm
  - MPV Mass: 14 kg

Subsystem	Component Name	Quantity
Structure	Pumpkin Supernova 6U	1
	Aluminum Shielding[1]	5

Stowed CubeSat Configuration



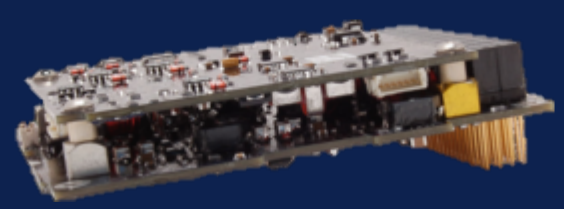


Pumpkin Supernova
6U aluminum structure

1. Shielding assumed to be 1.5 mm thick and covers all structure sides except cold gas thruster

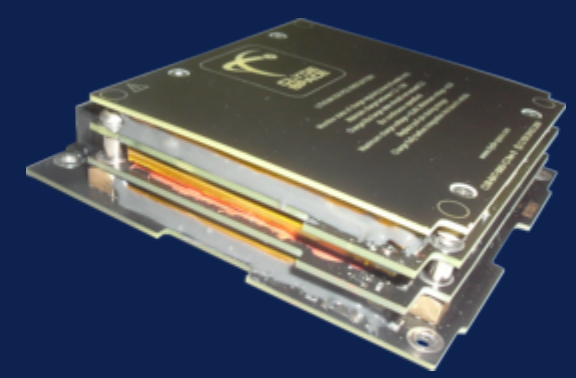
Electrical Power Subsystem

Subsystem	Component Name	Quantity
EPS	Clyde Space FLEX EPS	1
	CS 30 Whr Battery	2
	CS Deployable Double Sided 6U Panels	6
	CS 6U Body Mounted Solar Panels	2
	K/Ka-Band Reflectarray	1



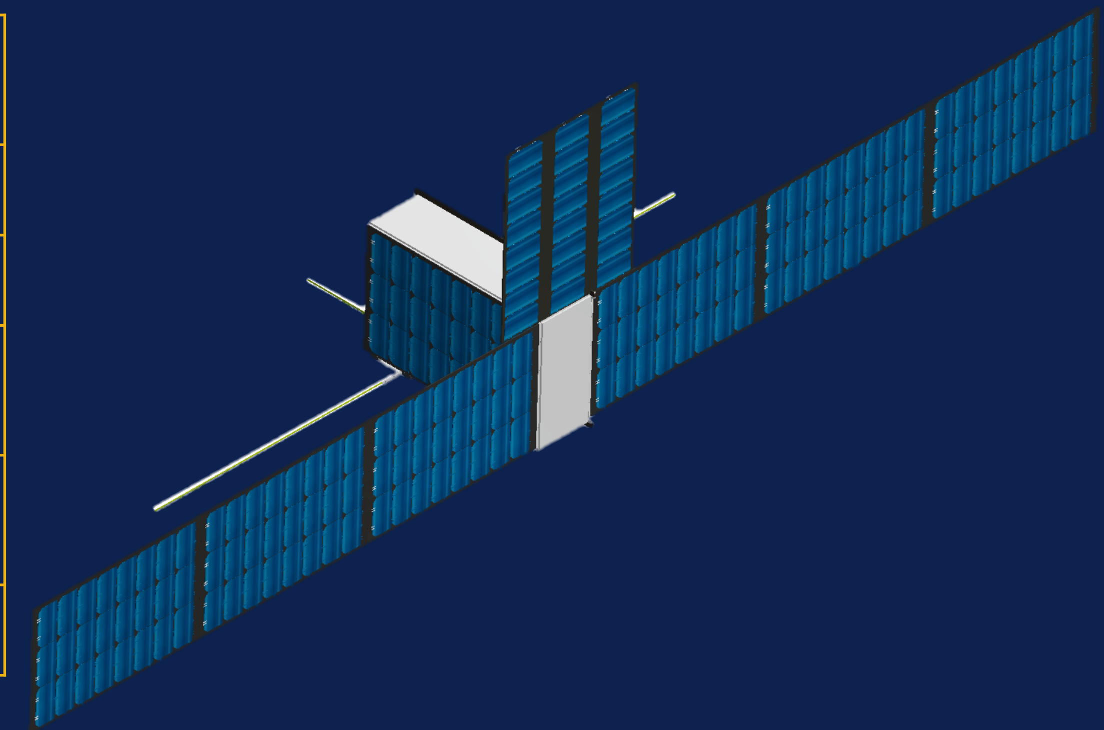
Clyde Space FLEX EPS

- 12 BCR inputs, enough for many solar panels
- On board over/under charge protection
- Placed in vault for radiation mitigation



Clyde Space Batteries

– 30 Whr batteries, sync with PDM board
– Built in heaters



Clyde Space Customized Solar Panels

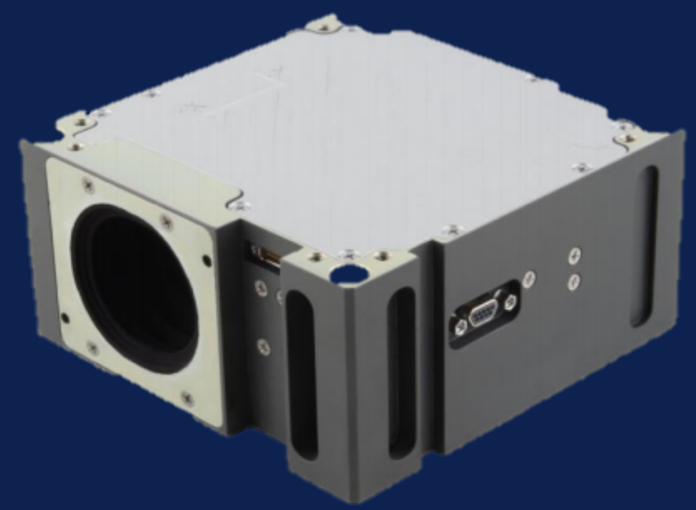
- 24 cells per face
  – 48 cells on one panel (double-sided)
- Solar Cell Efficiency: 28.3%
- Customization Required

K/Ka-Band Reflectarray (ISARA)

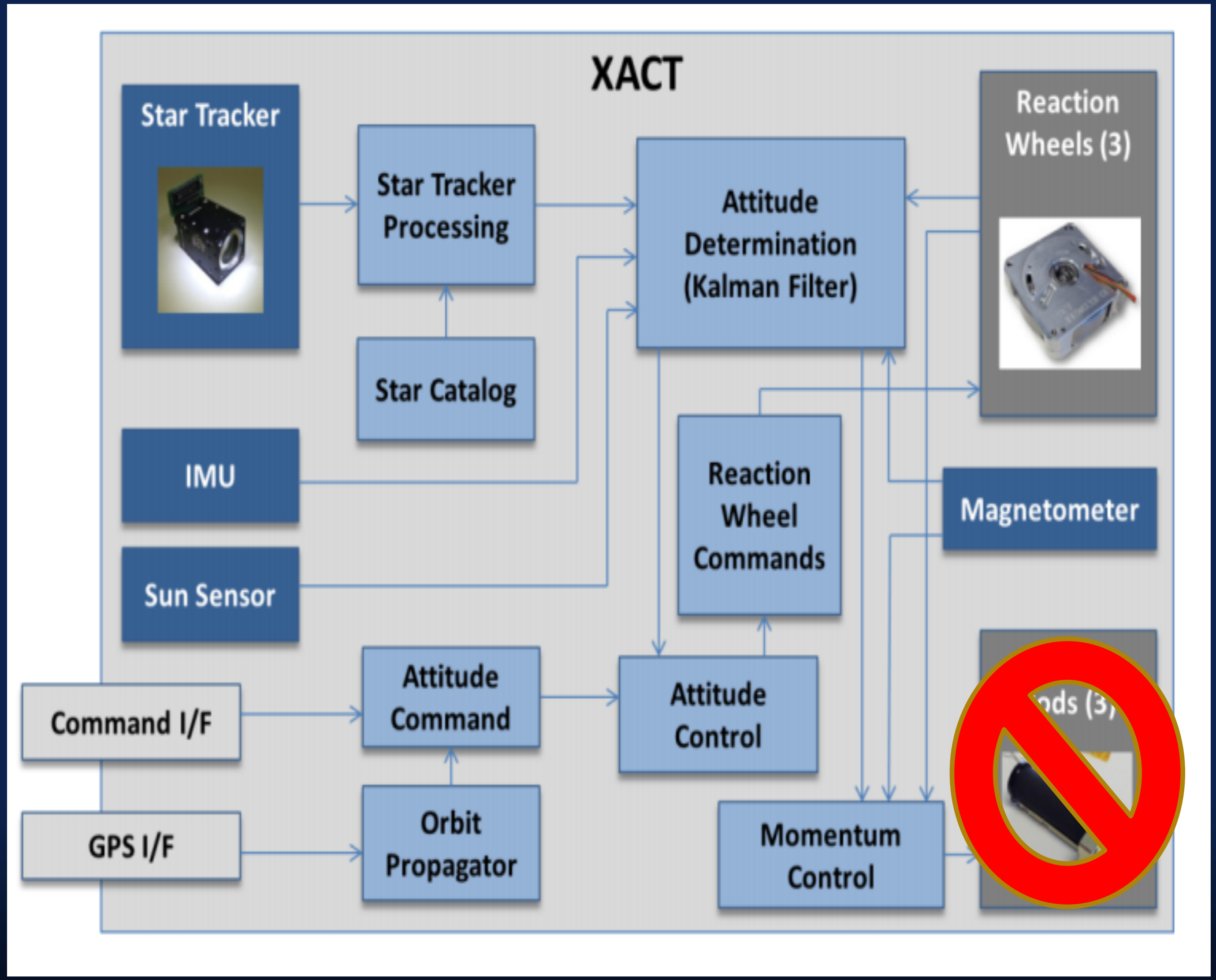
- 24 cells integrated into reflectarray

Attitude Determination & Control

Subsystem	Component Name	Quantity
ADCS	BCT-XACT Module	1



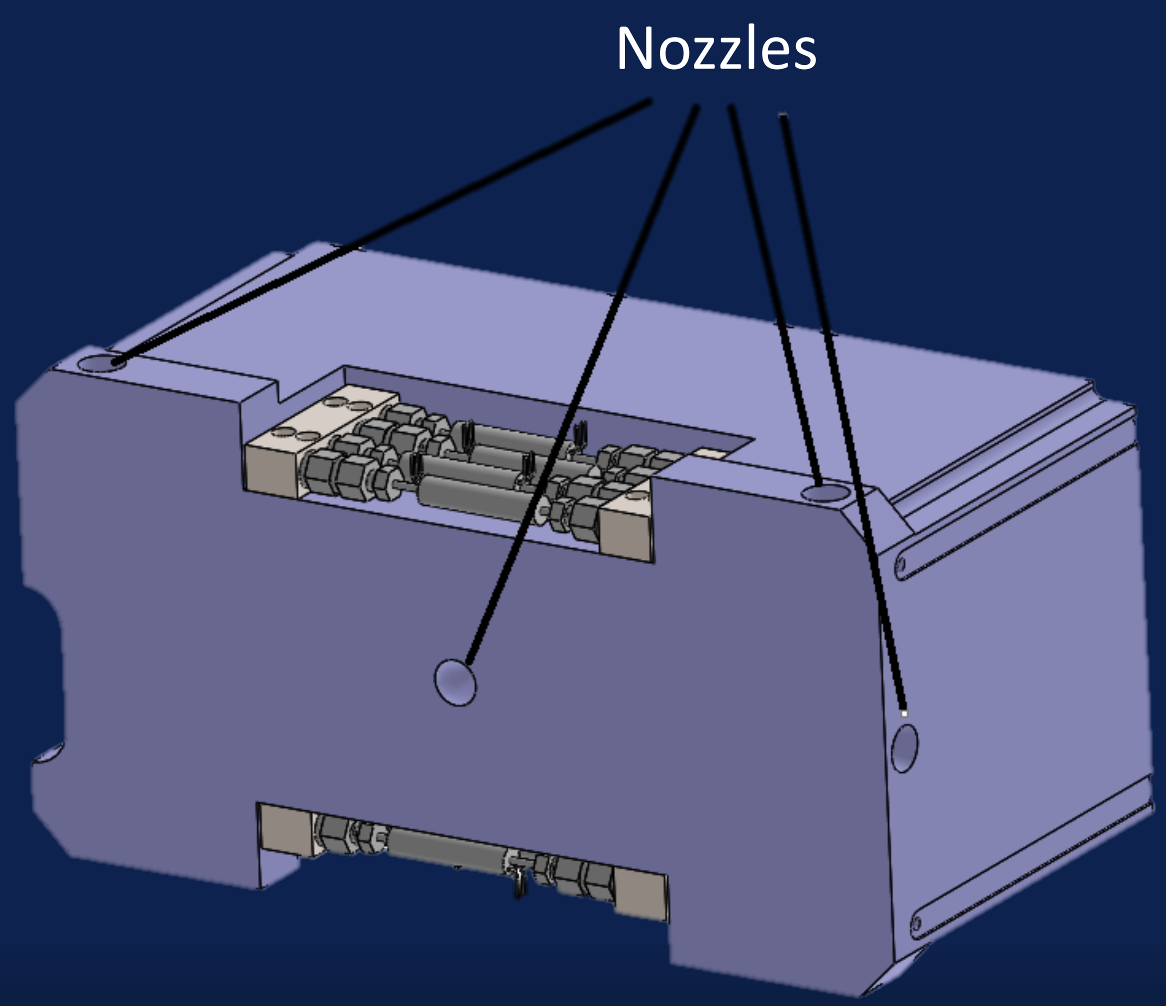
- Size: 0.5U
- Pointing Accuracy: ±0.003° (2 axes)
  ±0.007° (3rd axis)
- Low jitter 3-axis reaction wheel control
  - Desaturation with cold gas thruster
- Customizable software



Source: *Blue Canyon Technologies*

Propulsion

Subsystem	Component Name	Quantity
Propulsion	2U Cold Gas Thruster	1



Cold Gas Thruster CAD Model[1]

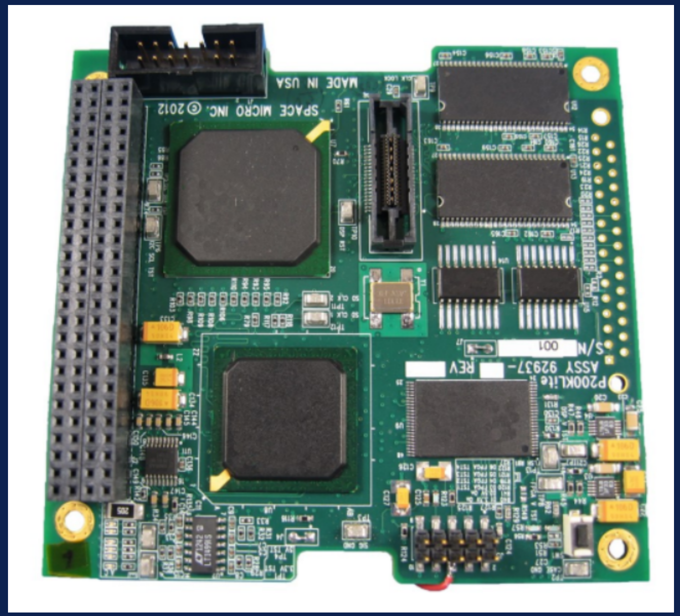
Thruster Characteristics	Value
Dimensions (mm)	21x10x10
Dry Mass (kg)	1.5
Propellant Mass (kg)	0.92
Propellant	R-236fa
Power (W)	0.85 (nominal) 14** (startup)
BOL Thrust* (mN)	40
Number of Nozzles	7
ΔV Capability (m/s)	31.5
I_{sp} (s)	50

[1]currently being developed by Georgia Tech Space Systems Design Laboratory

*per nozzle
** 2ms to open valve

Command & Data Handling

- Proton 200k-L (Space Micro)
  - Flight heritage on TACSAT-2
  - 1 GHz processor
  - 512 Mbyte SDRAM
  - 1.5W power draw
  - UART and GPIO interfaces



- Radiation Hardening
  - TID: 100krad (Si)
  - SEFI: 100% recoverable
  - SEL: > 63 LET
  - SEU: <1 per 1000 days in GEO

- FSW Architecture
  - Redundant software modules
  - Memory scrubbing
  - SEL and SEU detection
  - Reprogrammable on orbit

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Propellant Budget

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Maneuver	ΔV (m/s)	Propellant (g)
Orbit Transfer	22	614
Orbit Phasing	0.5	14
Orbit Maintenance	2.5	68
RW Desaturation	N/A	50
Reserves	6.5	222
Total	**31.5**	**920**

Assumptions

- Orbit transfer from 400 x 400 km orbit (injection from MTO) to 350 x 350 km orbit
- CubeSats phased 90 deg apart in orbit
- Orbit trim maneuvers once/month
- Reaction wheel desaturation allocation 50 g

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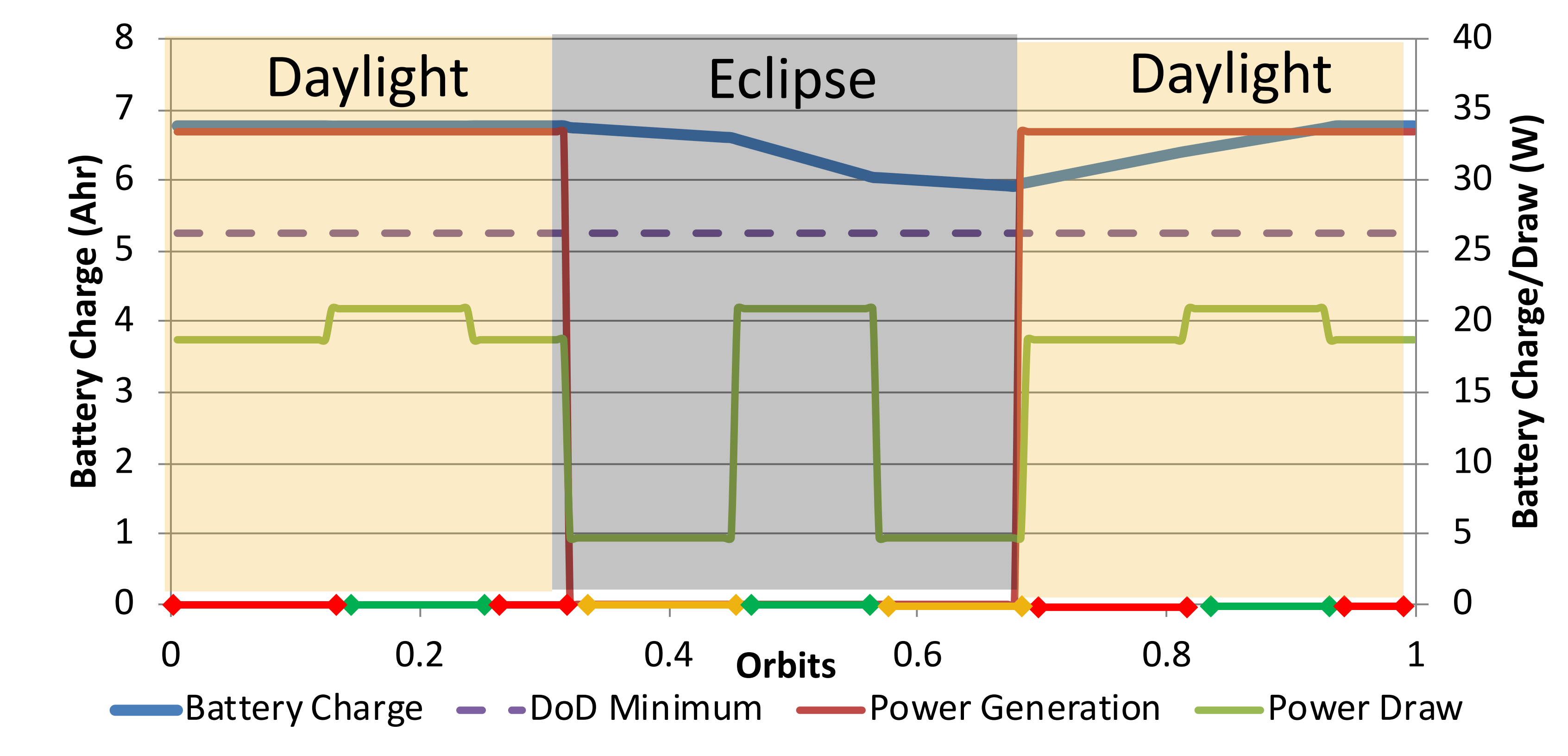
Power Budget

Subsystem	Component Name	Contingency (%)	Safe Mode Power Draw (mW)	Maneuvering Power Draw (mW)	UHF Rx/Tx Power Draw (mW)	DTE/DFE Power Draw (mW)
ADCS	BCT-XACT Module	10%	202	2024	2024	2024
Telecom	UHF Antenna	10%	220	0	2200	0
	IRIS v2 Transponder	25%	1475	1475	14750	14750
Propulsion	Cold Gas Thruster	25%	0	2706	0	0
C&DH	Proton 200k Lite	10%	1375	1375	1375	1375
EPS	CS FLEX EPS	10%	165	165	165	165
	CS 30 Whr Battery	10%	110	110	110	110
Thermal	Heaters	15%	1150	288	288	288
		MEV Total (W)	**4.70**	**8.14**	**20.91**	**18.71**

On-board Average Power Generation (W)	**33.42**

Battery Charge Cycle DoD Analysis



Results:

- 13% Battery Margin above DoD (5.25 Ahr)
- Clyde Space estimates 35000 cycle life → potentially over 4 year lifetime

<u>**Battery Specs (Clyde Space 30Whr):**</u>

- Quantity: 2
- Capacity: 7.5 Ahr
- Voltage: 8.2 V DC
- Rated DoD: 30% = 5.25 Ahr (lab tested for 5000 cycles)

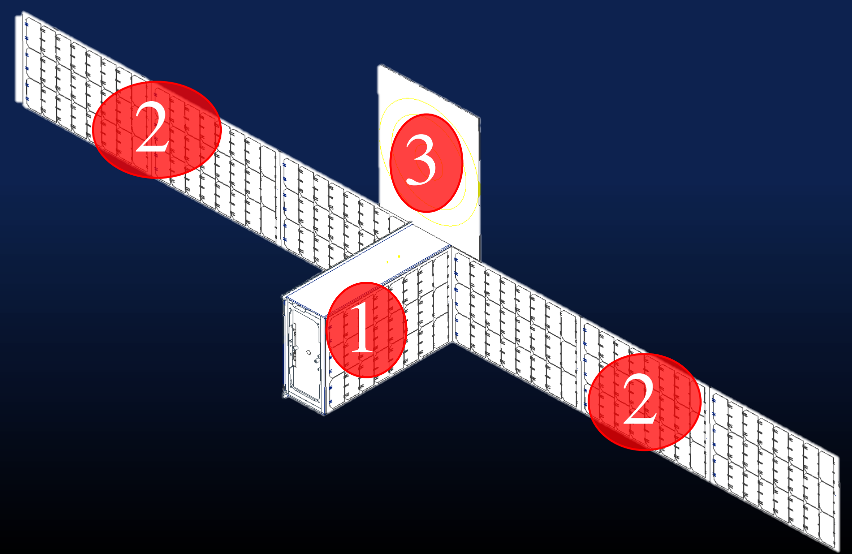
Operation Mode	Power Draw (W)	Power Generation (W)
UHF Rx/Tx	20.91	33.42 / 0
Safe (Eclipse)	4.70	0
DTE/DFE	18.71	33.42
Maneuvering	8.14	33.42

Thermal Control

- 3-Node thermal model applied at Mars
  - Finite differencing used to model temperature change with time
- Active thermal control provided by temp sensors and heaters
  - Single Mars Eclipse (42 min) during mission operation
  - 1 W Heaters applied when below -0° C
- Paint selection, MLI used to establish desired passive thermal characteristics
- Large deployable solar panels must be thermally isolated (kA ~ 4J/K)

Parameter	1	2	3
Primary Material	Aluminum	GaAs	Silicon
Surface Area (m^2)	0.266	0.912	0.178
Mass (kg)	8.67	2.00	0.59
Cp (J/kg*K)	897	350	700
Power (W)	33.42	0	0
Absorptivity	0.031	0.637	0.11
Emissivity	0.039	0.85	0.05
Thermal Conductivity (W/m*K)	167	52	148

Component Temperature Limit (°C)	0 - 40



Source: *Thermal Design and Analysis of Spacecraft, AFRL*

Thermal Control – Orbit In A Life Analysis

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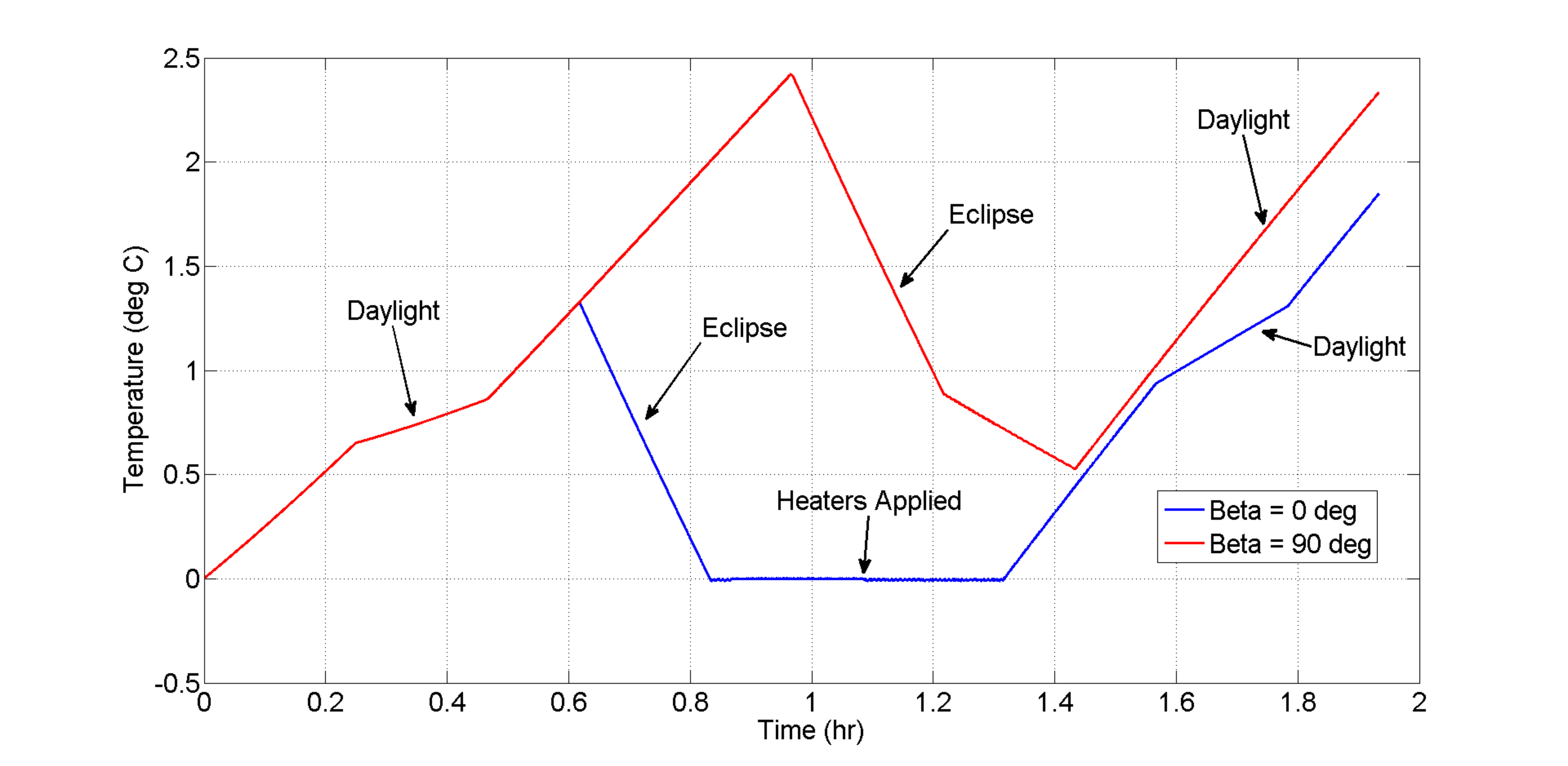

Equatorial Surface Asset Coverage Plot

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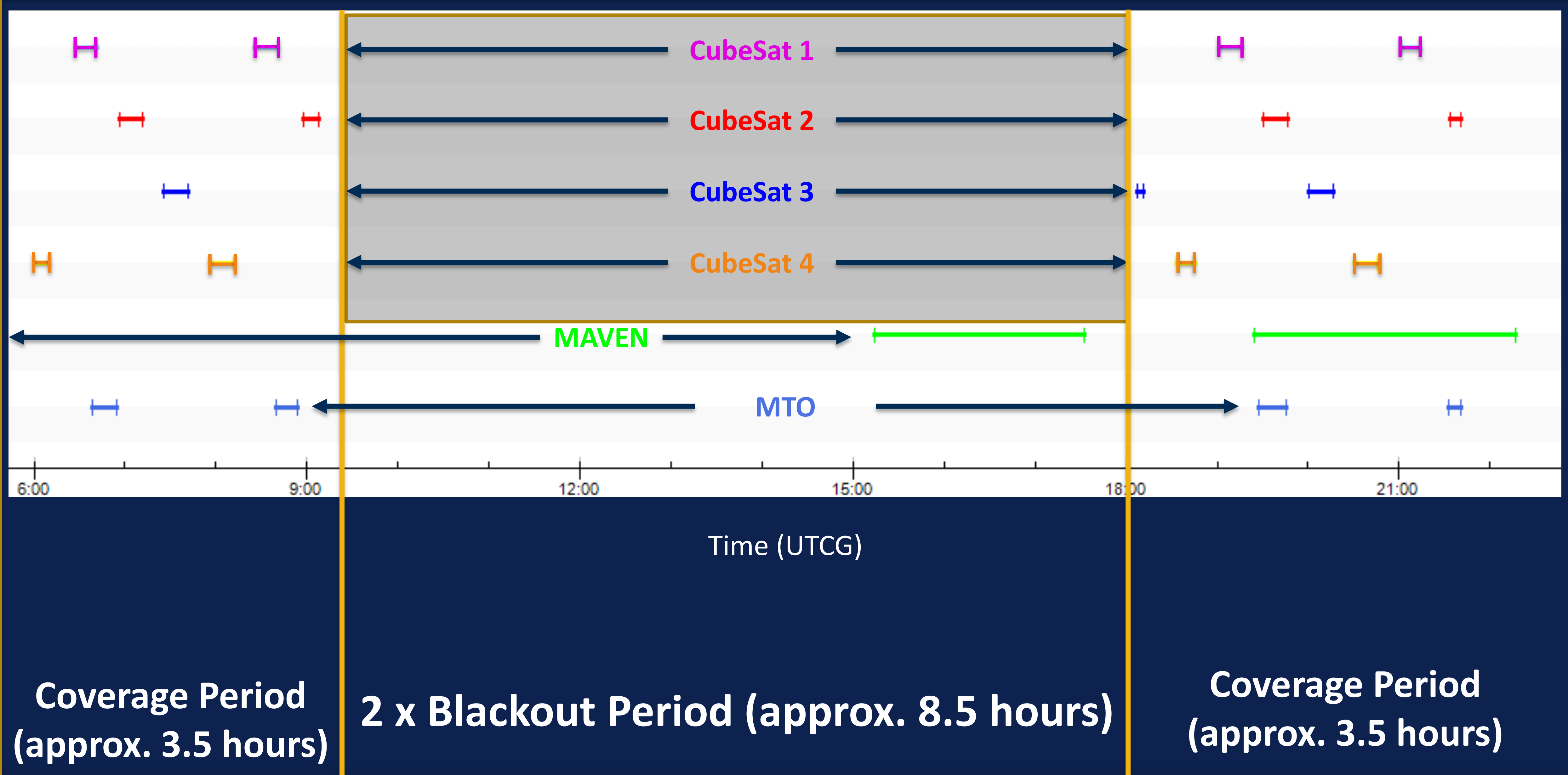
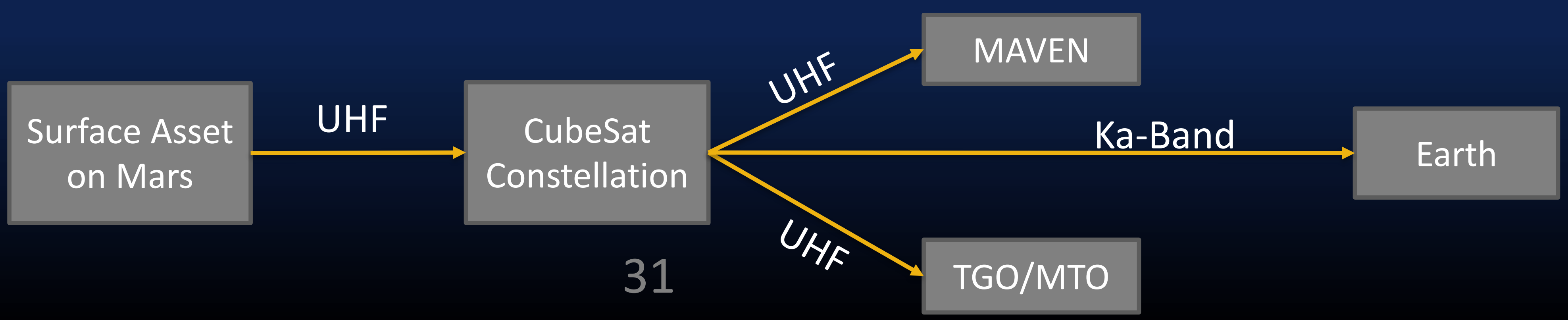


Variation in True Anomaly

4-CubeSat Constellation Return Link Capability

Variation in True Anomaly

CubeSat Constell. Inclination (deg)	Surface Asset Latitude (deg N)	CubeSat Constell. Avg # of Passes/Sol	CubeSat Avg. Pass Duration (min)	Surface to CubeSat Constell. Avg. Data Volume (Mb/Sol)	CubeSat Constell. Avg. Data Volume Per Sol via MAVEN (Mb/Sol)	CubeSat Constell. Avg. Data Volume Per Sol via TGO/MTO (Mb/Sol)	CubeSat Constell. Avg. Data Volume Per Sol DTE (Mb/Sol)
70	0	14.3	13.0	543	94	1142	342
70	10	14.6	13.0	553	94	1142	342
70	20	15.5	13.1	584	94	1142	342
0	0	45.7	17.5	3647	64	298	342
0	10	45.7	16.1	2373	64	298	342
0	20	45.7	10.8	914	64	298	342



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DTE Return Link Budget

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Best Case: 0.41 AU

Parameter	Value
Frequency (GHz)	32
RF Output (W)	2
CubeSat Antenna Gain (dBi)	33.5
Path Length (km)	6E07
34 m DSN Receive Gain (dBi)	79.5
Noise Temperature (K)	31
Data Rate (kbps)	28
Eb/No (dB)	7
Required Eb/No (dB)	**2**
Link Margin (dB)	**4**

Worst Case: 1 AU

Parameter	Value
Frequency (GHz)	32
RF Output (W)	2
CubeSat Antenna Gain (dBi)	33.5
Path Length (km)	4E08
34 m DSN Receive Gain (dBi)	79.5
Noise Temperature (K)	31
Data Rate (kbps)	4.7
Eb/No (dB)	7
Required Eb/No (dB)	**2**
Link Margin (dB)	**4**

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DFE Forward Link Budget

Best Case: 0.41 AU

Parameter	Value
Frequency (GHz)	32
RF Output (W)	800
34m DSN Gain (dBi)	79.5
Path Length (km)	6E07
CubeSat Receive Gain (dBi)	33.5
Noise Temperature (K)	80
Data Rate (kbps)	100
Eb/No (dB)	7
Required Eb/No (dB)	**2**
Link Margin (dB)	**20.3**

Worst Case: 1 AU

Parameter	Value
Frequency (GHz)	32
RF Output (W)	800
34m DSN Gain (dBi)	79.5
Path Length (km)	4E08
CubeSat Receive Gain (dBi)	33.5
Noise Temperature (K)	80
Data Rate (kbps)	100
Eb/No (dB)	7
Required Eb/No (dB)	**2**
Link Margin (dB)	**12.6**

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UHF Crosslink Return Link Budget

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TGO/M22 → CubeSat

Parameter	Value
Frequency (MHz)	435
RF Output (W)	1
Orbiter Antenna Gain (dBi)	3
Average Path Length (km)	1,513
CubeSat Receive Gain (dBi)	0
Noise Temperature (K)	500
Data Rate (kbps)	25.7
Eb/No (dB)	12.6
Required Eb/No (dB)	**9.6**
Link Margin (dB)	**2**

MAVEN → CubeSat

Parameter	Value
Frequency (MHz)	435
RF Output (W)	1
Orbiter Antenna Gain (dBi)	3
Average Path Length (km)	5,286
CubeSat Receive Gain (dBi)	0
Noise Temperature (K)	500
Data Rate (kbps)	2.1
Eb/No (dB)	12.6
Required Eb/No (dB)	**9.6**
Link Margin (dB)	**2**

UHF Crosslink Forward Link Budget

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CubeSat → TGO/M22

Parameter	Value
Frequency (MHz)	435
RF Output (W)	0.5
CubeSat Antenna Gain (dBi)	0
Average Path Length (km)	1,513
Orbiter Receive Gain (dBi)	3
Noise Temperature (K)	500
Data Rate (kbps)	12.9
Eb/No (dB)	12.6
Required Eb/No (dB)	**9.6**
Link Margin (dB)	**2**

CubeSat → MAVEN

Parameter	Value
Frequency (MHz)	435
RF Output (W)	0.5
CubeSat Antenna Gain (dBi)	0
Average Path Length (km)	5,286
Orbiter Receive Gain (dBi)	3
Noise Temperature (K)	500
Data Rate (kbps)	1.1
Eb/No (dB)	12.6
Required Eb/No (dB)	**9.6**
Link Margin (dB)	**2**

Surface-to-CubeSat Return Link Budget

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Best Case: 0° Surface Asset

Parameter	Value
Frequency (MHz)	435
RF Output (W)	1
Electra Antenna Gain (dBi)	3
Path Length (km)	1101
CubeSat Receive Gain (dBi)	0
Noise Temperature (K)	500
Data Rate (kbps)	48.6
Eb/No (dB)	12.6
Required Eb/No (dB)	**9.6**
Link Margin (dB)	**2**

Worst Case: 20° Surface Asset

Parameter	Value
Frequency (MHz)	435
RF Output (W)	1
Electra Antenna Gain (dBi)	3
Path Length (km)	1108
CubeSat Receive Gain (dBi)	0
Noise Temperature (K)	500
Data Rate (kbps)	48.0
Eb/No (dB)	12.6
Required Eb/No (dB)	**9.6**
Link Margin (dB)	**2**

CubeSat-to-Surface Forward Link Budget

Best Case: 0° Surface Asset

Parameter	Value
Frequency (MHz)	435
RF Output (W)	0.5
CubeSat Antenna Gain (dBi)	0
Average Path Length (km)	1101
Surface Receive Gain (dBi)	3
Noise Temperature (K)	255
Data Rate (kbps)	47.6
Eb/No (dB)	12.6
Required Eb/No (dB)	**9.6**
Link Margin (dB)	**2**

Worst Case: 20° Surface Asset

Parameter	Value
Frequency (MHz)	435
RF Output (W)	0.5
CubeSat Antenna Gain (dBi)	0
Average Path Length (km)	1108
Surface Receive Gain (dBi)	3
Noise Temperature (K)	255
Data Rate (kbps)	47.0
Eb/No (dB)	12.6
Required Eb/No (dB)	**9.6**
Link Margin (dB)	**2**

Georgia Tech SSDL

NASA JPL Jet Propulsion Laboratory California Institute of Technology

Flight System Deployed Configuration (KaPDA Version)

- Motivation/ Background
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- **Flight System**
- Telecom Relay Performance
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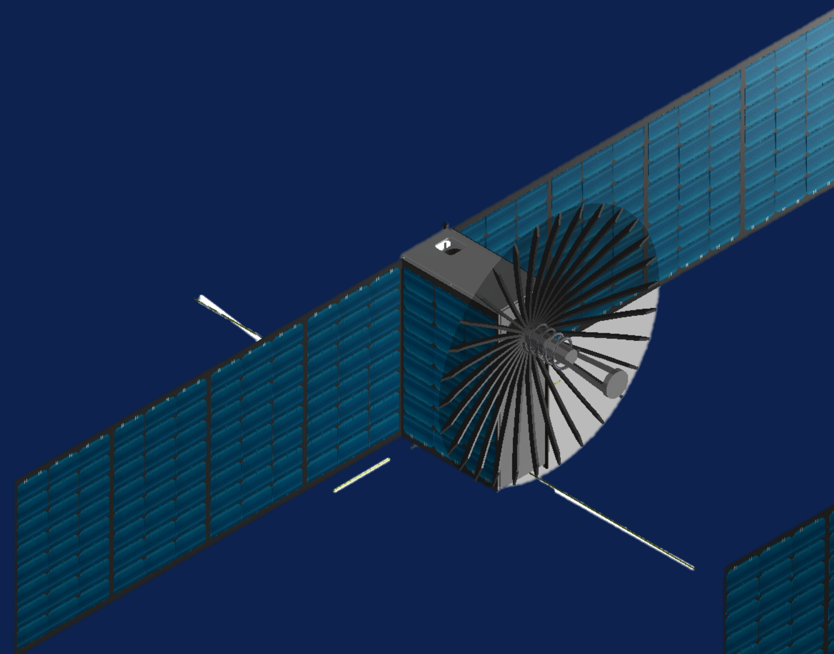
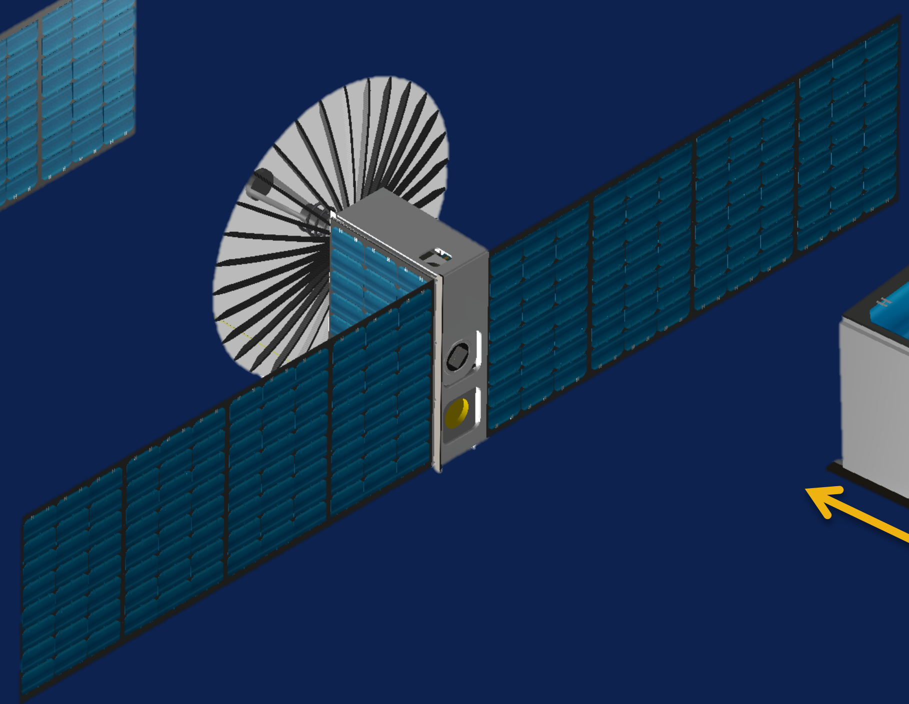
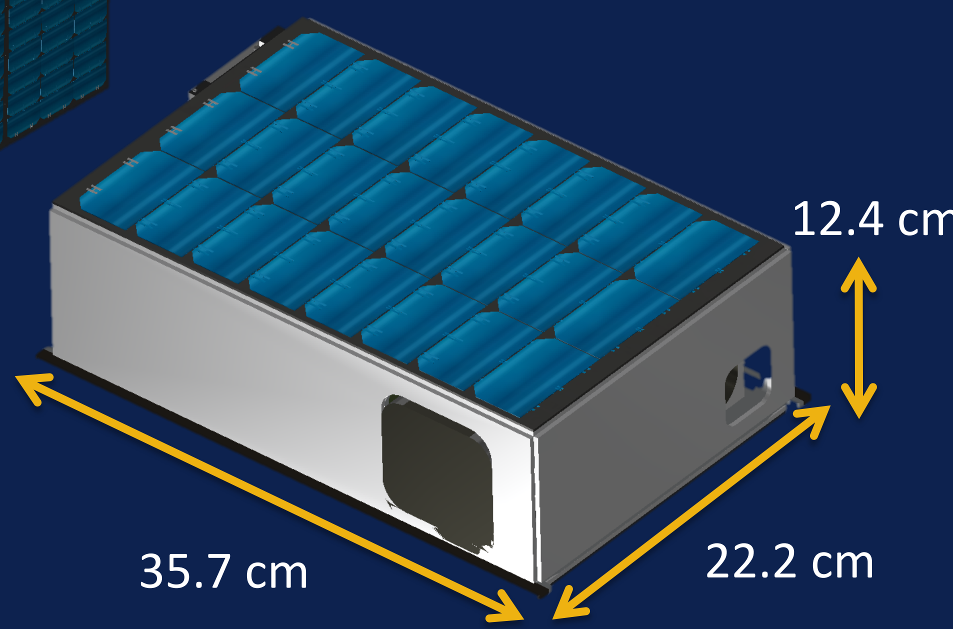


Front Isometric View



Back Isometric View



Stowed Isometric View

Radiation Mitigation

- The Mars CubeSat design will advance the CubeSat standard for radiation tolerance to enable a two Mars-year baseline mission
- Approaches to radiation mitigation:
  - Shielding
  - Radiation hardened electronics
  - Selected hardware redundancy
  - Software redundancy
  - Memory scrubbing
  - Fault tolerance by design

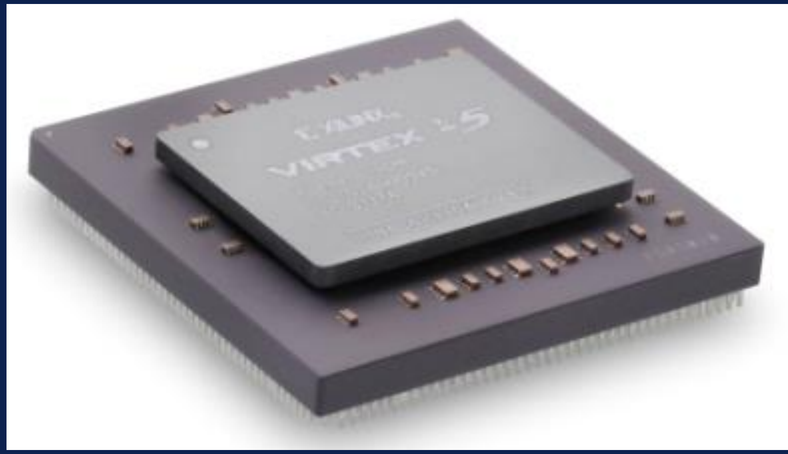
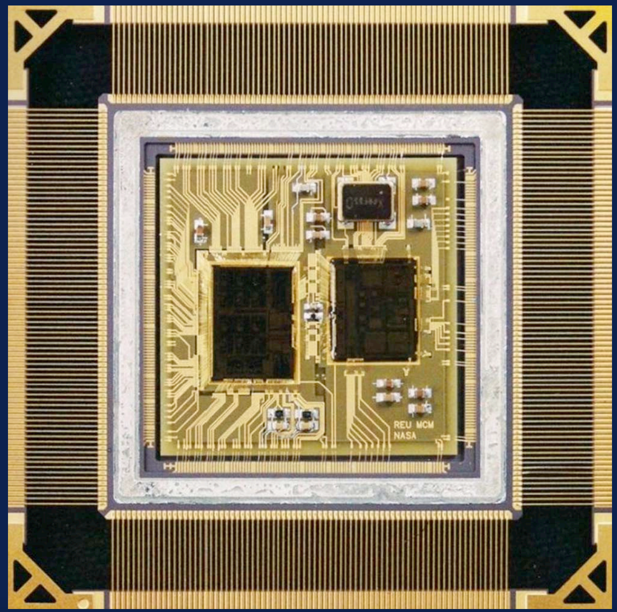


Image Credit: Xilinx



Source: Cressler, *Radiation effects in SiGe Technology*

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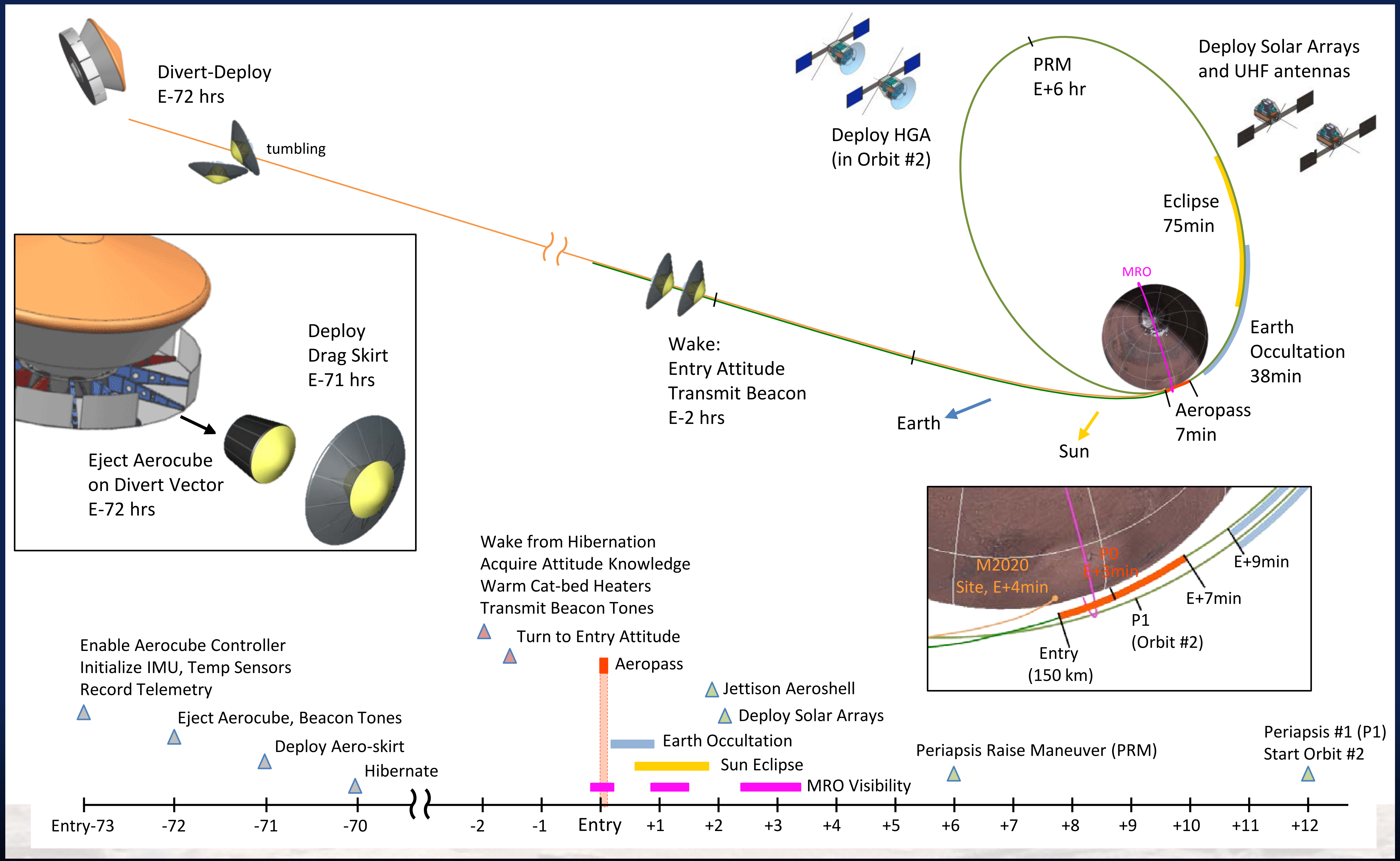
Mars Aerocapture Concept



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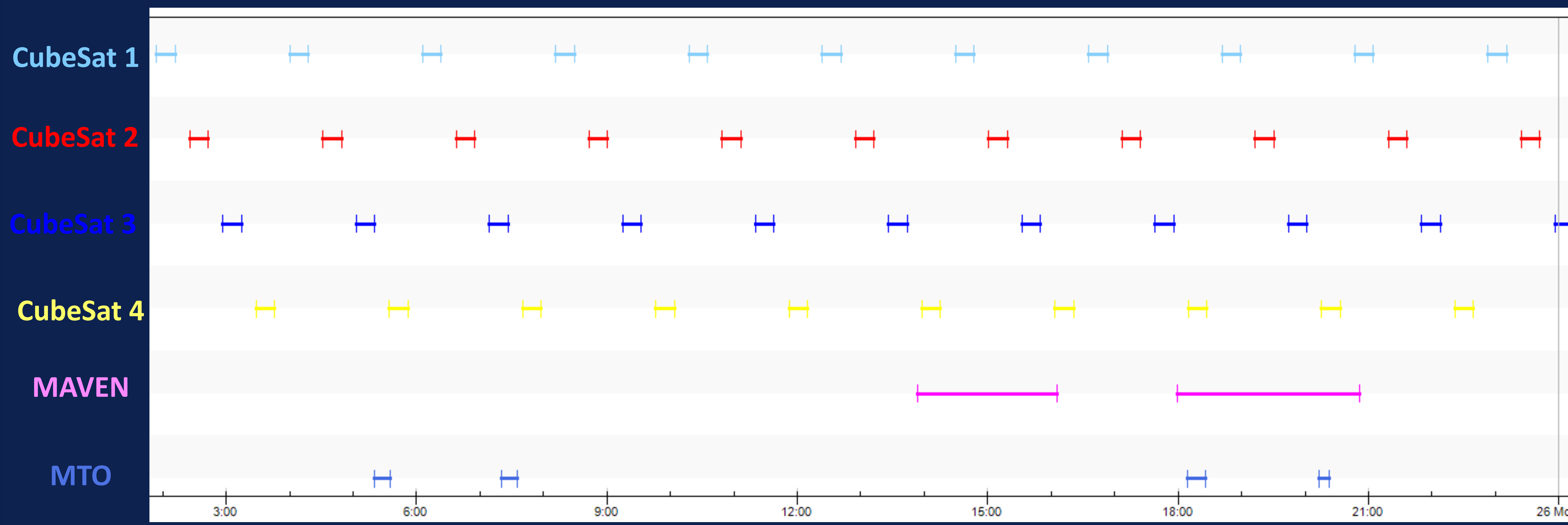
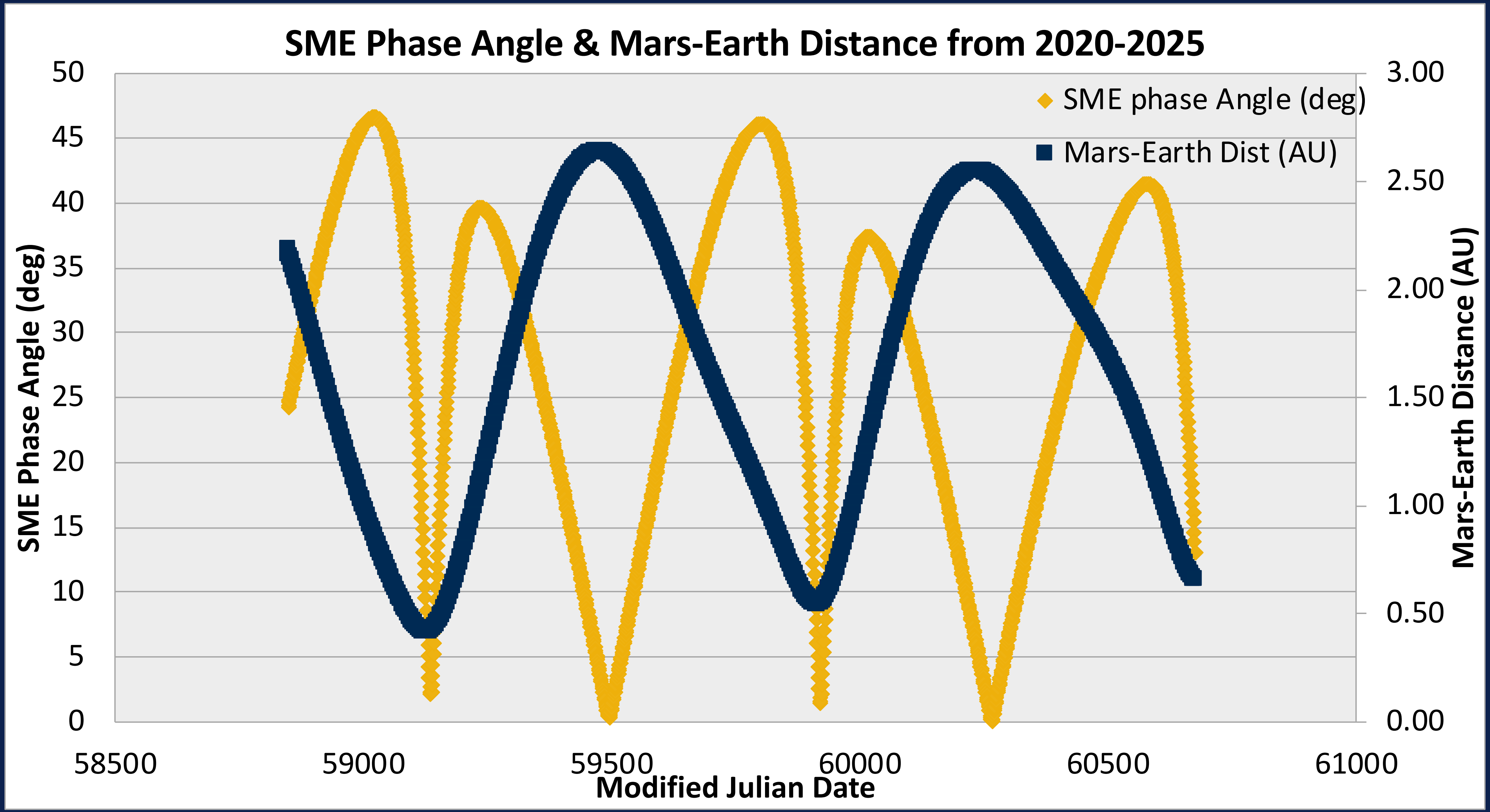
Equatorial Surface Asset Coverage Plot: 0° Inclination Constellation



- Full coverage of equatorial surface assets
  - Maximum access gap time of 14 mins between different relays
- CubeSat Relay averages 45 passes/Sol compared to MTO, 4 passes/Sol

Mars Ephemeris Data Analysis



Max Earth-Mars Distance (AU)	2.64
Min Earth-Mars Distance (AU)	0.41
Max Phase Angle (°)	46.594