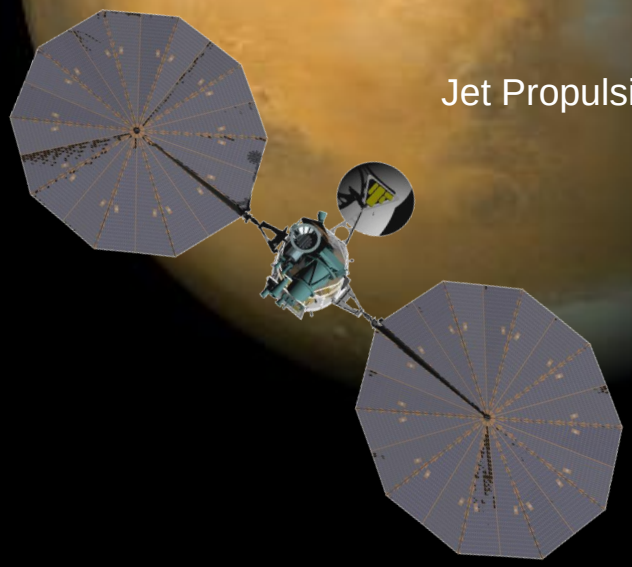
Jet Propulsion Laboratory
California Institute of Technology

Solar Electric Propulsion for Mars Mission Applications

Ryan Woolley, Austin Nicholas, Rob Lock, and Theresa Kowalkowski

Jet Propulsion Laboratory, California Institute of Technology



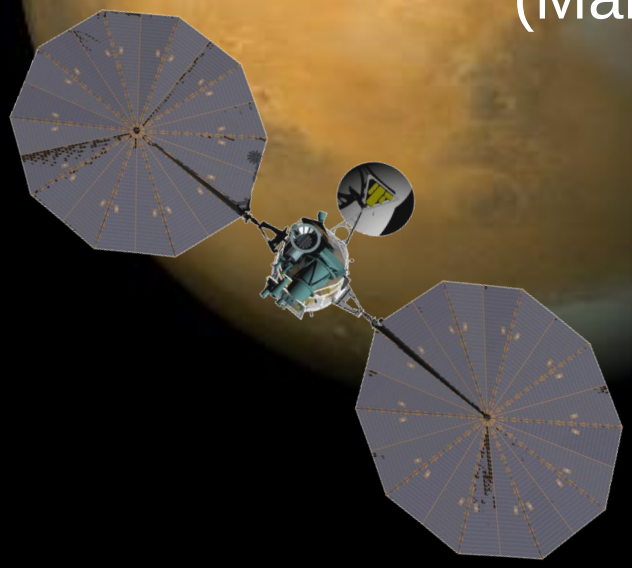
20th Advanced Space Propulsion Workshop
November 17-19, 2014

Overview

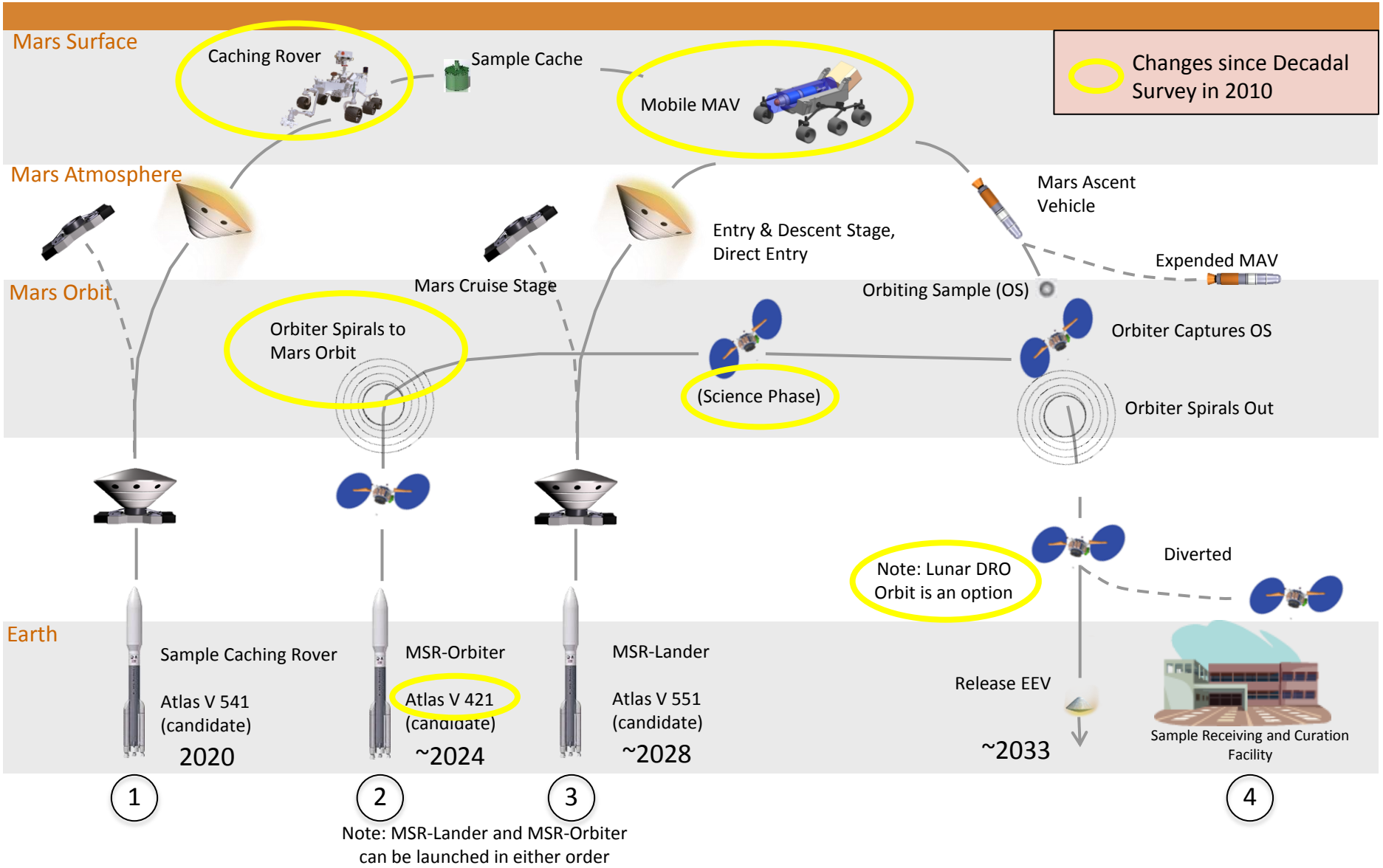
- Where Are We Now?
  - Mars Sample Return (MSR) and the Sample Return Orbiter (SRO)
  - Orbiter team's design tools and baseline mission
- Mission Design for SRO
  - Database of trajectories
  - Key outputs / figures / interesting findings
- Benefits of using SEP
  - Reference mission
  - Comparison with ballistic mission
- Future Work
  - Other SEP mission architectures
  - Current studies

Where Are We Now?

(Mars Formulation and MSR)



Current MSR Concept



PRE-DECISION DRAFT: For Planning and Discussion Purposes Only

Why SEP for Mars?

- Solar Electric Propulsion offers high Isp (5-10 x Biprop)
- SEP for basic orbiter missions is a hard sell
- SEP shines in high ΔV missions (i.e. Mars Sample Return)

Other benefits of SEP:

– High maturity of SEP thrusters (BPT-4000)

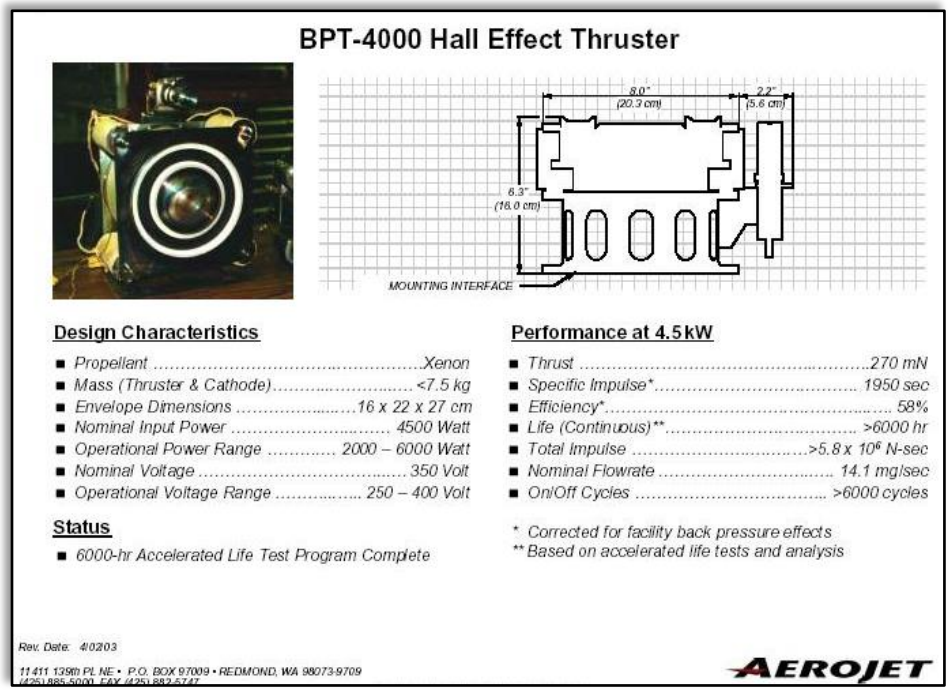
More Flexibility

- Trade-able parameters:
  - mass
  - power
  - flight time
- Long launch periods
- Launch Year robustness

Risk Reduction

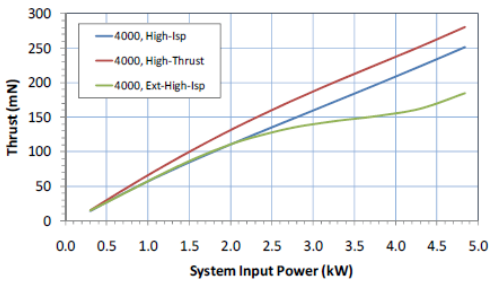
- No critical events
  - No MOI
  - No aerobraking
  - No TEI
- Tailor arrival conditions at Earth
- Flexible margins

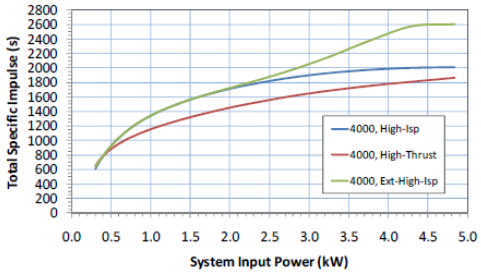
Aerojet BPT- 4000



Isp:	1800 – 2000 sec
Thrust:	0.25 N
Eff.:	50 – 55%
Power:	0.3 – 4.8 kW

- Can be run in high thrust or high Isp modes
- Successfully flown on Advanced EHF satellites
- Highest power SEP engine flown to date



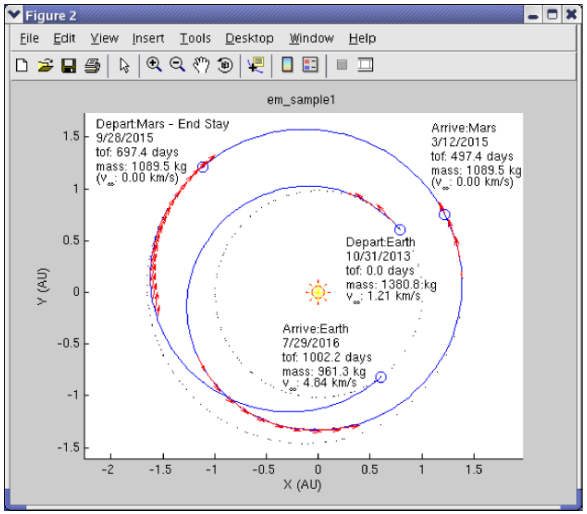


From AIAA 2010-6623, Hofer (2010)

Mission Design Work

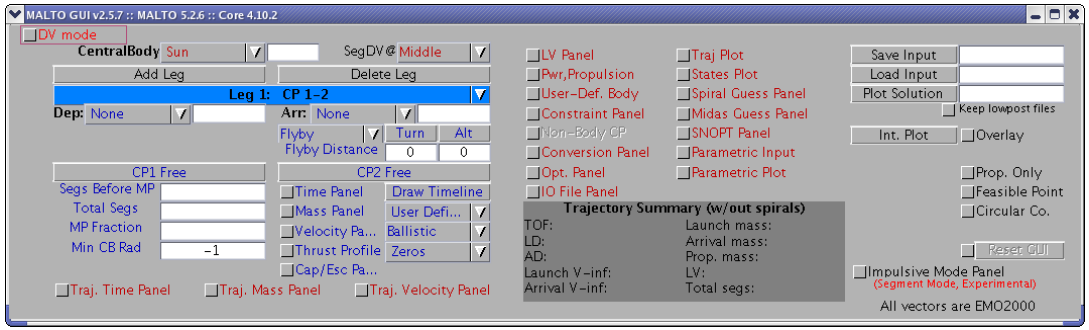
MALTO Software

- Mission Analysis Low-Thrust Optimization
- Developed at JPL
- Fast, medium-fidelity
- Simulates low-thrust via multi-segment, 2-body impulsive maneuvers
- Core in FORTRAN 95, GUI and post processing in MATLAB
- Spiral to/from Mars added analytically



Benefits

- Fast
- Robust convergence
- Parametric mode
- Accurate results



"Great Taste, Better Value"*

**This slogan is a trademark of Malt-O-Meal Company*

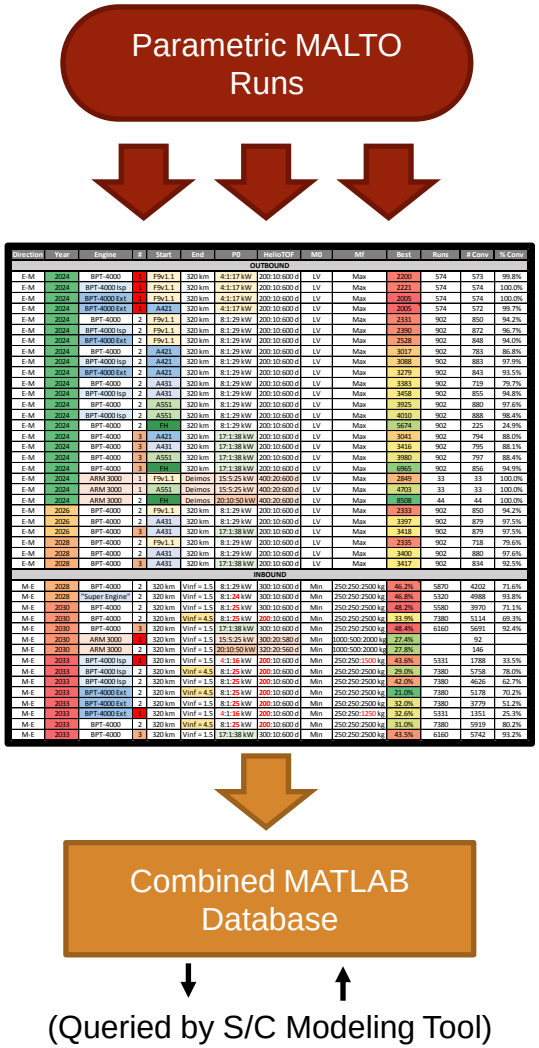
The Trade Space

Parameter	Value(s)
Launch Vehicle	F9 1.1, **Atlas V 421**, 431, 551, *FH*
Launch Years	2022, **2024**, 2026, 2028
Return Years	2028, 2030, **2033**, 2035
Engines (#)	**BPT-4000** (**2**-3), others
Duty Cycle	95%
Spacecraft Bus Power	700 W
Post-Launch Coast	30 days
Pre-Earth-Arrival Coast	30 days
Mars Science Orbit Altitude (circular)	320 km
Earth Arrival V_∞	**1.5 km/s**, 4.5 km/s
Power Levels	8 – 29 kW (38 kW for 3 engines)
Heliocentric TOF	200 – 600 days

MALTO is run in parametric mode to loop through as many cases as possible

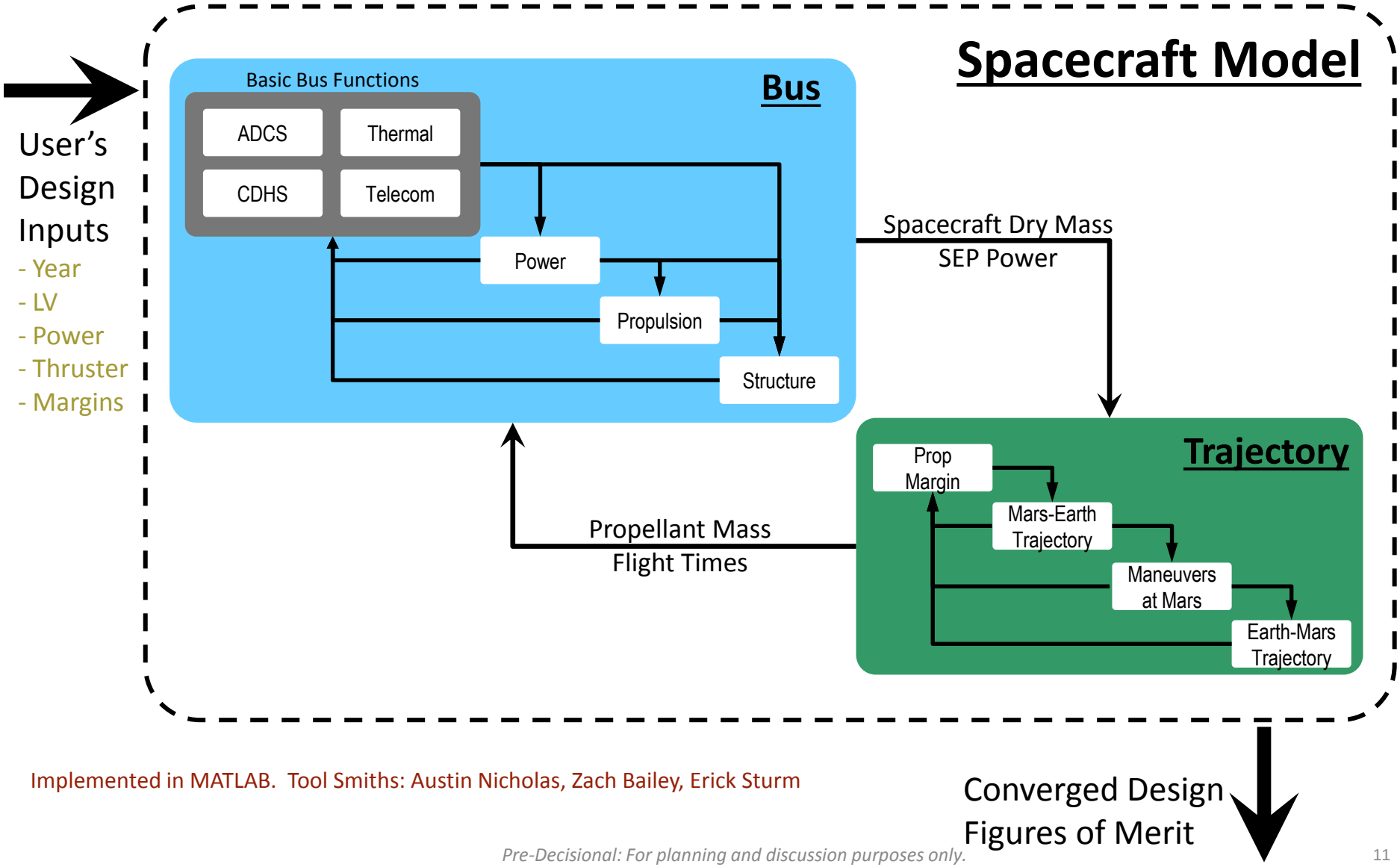
MALTO Database Runs

- So far we have run:
  - 21,348 Outbound cases
  - 84,032 Inbound cases
- Dozens of case configurations
  - Mostly varied around baseline
  - Case configurations tracked in Excel spreadsheet (right)
- Typical case run times
  - 1-3 hours (outbound)
  - 3-15 hours (inbound)
- Thousands of runs added daily



Direction	Year	Engine	#	Start	End	P0	Hmin/DF	M0	Mf	Best	Runs	# Conv	%Conv
OUTBOUND													
E-M	2024	BPT-4000	1	F9v1.1	320 km	4:1:17 kW	200:10:600 d	LV	Max	2200	574	573	99.8%
E-M	2024	BPT-4000 Isp	1	F9v1.1	320 km	4:1:17 kW	200:10:600 d	LV	Max	2221	574	574	100.0%
E-M	2024	BPT-4000 Ext	1	F9v1.1	320 km	4:1:17 kW	200:10:600 d	LV	Max	2005	574	574	100.0%
E-M	2024	BPT-4000 Ext	1	A421	320 km	4:1:17 kW	200:10:600 d	LV	Max	2005	574	572	99.7%
E-M	2024	BPT-4000	2	F9v1.1	320 km	8:1:29 kW	200:10:600 d	LV	Max	2331	902	850	94.2%
E-M	2024	BPT-4000 Isp	2	F9v1.1	320 km	8:1:29 kW	200:10:600 d	LV	Max	2390	902	872	96.7%
E-M	2024	BPT-4000 Ext	2	F9v1.1	320 km	8:1:29 kW	200:10:600 d	LV	Max	2528	902	848	94.0%
E-M	2024	BPT-4000	2	A421	320 km	8:1:29 kW	200:10:600 d	LV	Max	3017	902	783	86.8%
E-M	2024	BPT-4000 Isp	2	A421	320 km	8:1:29 kW	200:10:600 d	LV	Max	3088	902	883	97.9%
E-M	2024	BPT-4000 Ext	2	A421	320 km	8:1:29 kW	200:10:600 d	LV	Max	3279	902	843	93.5%
E-M	2024	BPT-4000	2	A431	320 km	8:1:29 kW	200:10:600 d	LV	Max	3383	902	719	79.7%
E-M	2024	BPT-4000 Isp	2	A431	320 km	8:1:29 kW	200:10:600 d	LV	Max	3458	902	855	94.8%
E-M	2024	BPT-4000	2	A551	320 km	8:1:29 kW	200:10:600 d	LV	Max	3925	902	880	97.6%
E-M	2024	BPT-4000 Isp	2	A551	320 km	8:1:29 kW	200:10:600 d	LV	Max	4010	902	888	98.4%
E-M	2024	BPT-4000	2	FH	320 km	8:1:29 kW	200:10:600 d	LV	Max	5674	902	225	24.9%
E-M	2024	BPT-4000	3	A421	320 km	17:1:38 kW	200:10:600 d	LV	Max	3041	902	794	88.0%
E-M	2024	BPT-4000	3	A431	320 km	17:1:38 kW	200:10:600 d	LV	Max	3416	902	795	88.1%
E-M	2024	BPT-4000	3	A551	320 km	17:1:38 kW	200:10:600 d	LV	Max	3980	902	797	88.4%
E-M	2024	BPT-4000	3	FH	320 km	17:1:38 kW	200:10:600 d	LV	Max	6965	902	856	94.9%
E-M	2024	ARM 3000	1	F9v1.1	Deimos	15:5:25 kW	400:20:600 d	LV	Max	2849	33	33	100.0%
E-M	2024	ARM 3000	1	A551	Deimos	15:5:25 kW	400:20:600 d	LV	Max	4703	33	33	100.0%
E-M	2024	ARM 3000	2	FH	Deimos	20:10:50 kW	400:20:600 d	LV	Max	6508	44	44	100.0%
E-M	2026	BPT-4000	2	F9v1.1	320 km	8:1:29 kW	200:10:600 d	LV	Max	2333	902	850	94.2%
E-M	2026	BPT-4000	2	A431	320 km	8:1:29 kW	200:10:600 d	LV	Max	3397	902	879	97.5%
E-M	2026	BPT-4000	3	A431	320 km	17:1:38 kW	200:10:600 d	LV	Max	3418	902	879	97.5%
E-M	2028	BPT-4000	2	F9v1.1	320 km	8:1:29 kW	200:10:600 d	LV	Max	2335	902	718	79.6%
E-M	2028	BPT-4000	2	A431	320 km	8:1:29 kW	200:10:600 d	LV	Max	3400	902	880	97.6%
E-M	2028	BPT-4000	3	A431	320 km	17:1:38 kW	200:10:600 d	LV	Max	3417	902	834	92.5%
INBOUND													
M-E	2028	BPT-4000	2	320 km	Vinf = 1.5	8:1:29 kW	300:10:600 d	Min	250:250:2500 kg	46.2%	5870	4202	71.6%
M-E	2028	"Super Engine"	2	320 km	Vinf = 1.5	8:1:24 kW	300:10:600 d	Min	250:250:2500 kg	46.8%	5320	4988	93.8%
M-E	2030	BPT-4000	2	320 km	Vinf = 1.5	8:1:25 kW	300:10:600 d	Min	250:250:2500 kg	48.2%	5580	3970	71.1%
M-E	2030	BPT-4000	2	320 km	Vinf = 4.5	8:1:25 kW	200:10:600 d	Min	250:250:2500 kg	33.9%	7380	5114	69.3%
M-E	2030	BPT-4000	3	320 km	Vinf = 1.5	17:1:38 kW	300:10:600 d	Min	250:250:2500 kg	48.4%	6160	5691	92.4%
M-E	2030	ARM 3000	1	320 km	Vinf = 1.5	15:5:25 kW	300:20:580 d	Min	1000:500:2000 kg	27.4%		92	
M-E	2030	ARM 3000	2	320 km	Vinf = 1.5	20:10:50 kW	320:20:560 d	Min	1000:500:2000 kg	27.8%		146	
M-E	2033	BPT-4000 Isp	1	320 km	Vinf = 1.5	4:1:16 kW	200:10:600 d	Min	250:250:1500 kg	43.6%	5331	1788	33.5%
M-E	2033	BPT-4000 Isp	2	320 km	Vinf = 4.5	8:1:25 kW	200:10:600 d	Min	250:250:2500 kg	29.0%	7380	5758	78.0%
M-E	2033	BPT-4000 Isp	2	320 km	Vinf = 1.5	8:1:25 kW	200:10:600 d	Min	250:250:2500 kg	42.0%	7380	4626	62.7%
M-E	2033	BPT-4000 Ext	2	320 km	Vinf = 4.5	8:1:25 kW	200:10:600 d	Min	250:250:2500 kg	21.0%	7380	5178	70.2%
M-E	2033	BPT-4000 Ext	2	320 km	Vinf = 1.5	8:1:25 kW	200:10:600 d	Min	250:250:2500 kg	32.0%	7380	3779	51.2%
M-E	2033	BPT-4000 Ext	1	320 km	Vinf = 1.5	4:1:16 kW	200:10:600 d	Min	250:250:1250 kg	32.6%	5331	1351	25.3%
M-E	2033	BPT-4000	2	320 km	Vinf = 4.5	8:1:25 kW	200:10:600 d	Min	250:250:2500 kg	31.0%	7380	5919	80.2%
M-E	2033	BPT-4000	3	320 km	Vinf = 1.5	17:1:38 kW	300:10:600 d	Min	250:250:2500 kg	43.5%	6160	5742	93.2%

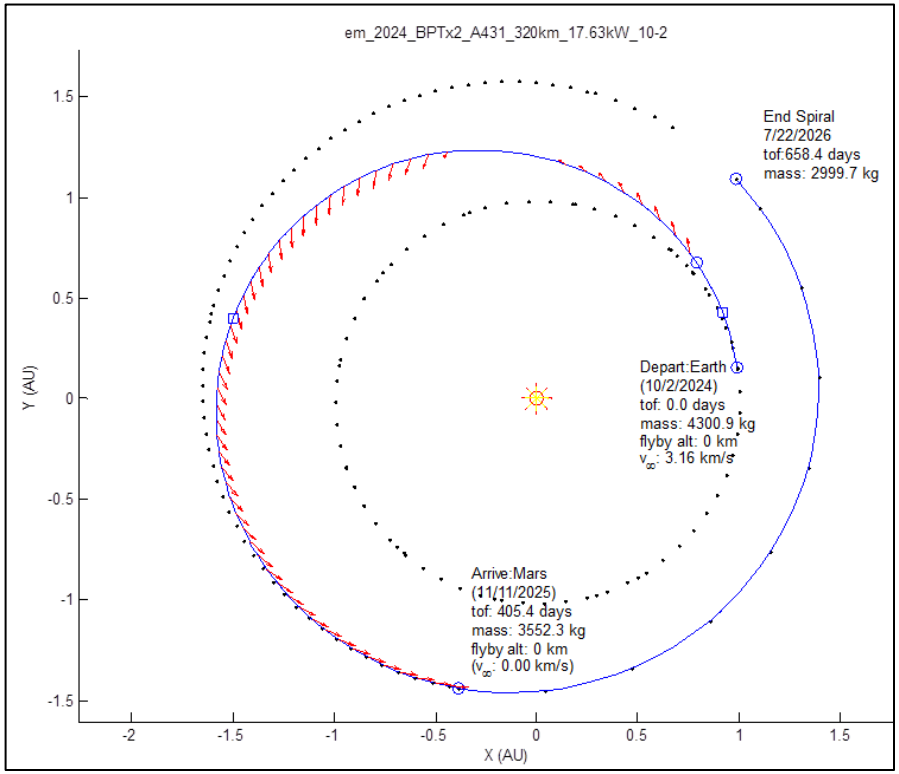
SRO Spacecraft Modeling



Implemented in MATLAB. Tool Smiths: Austin Nicholas, Zach Bailey, Erick Sturm

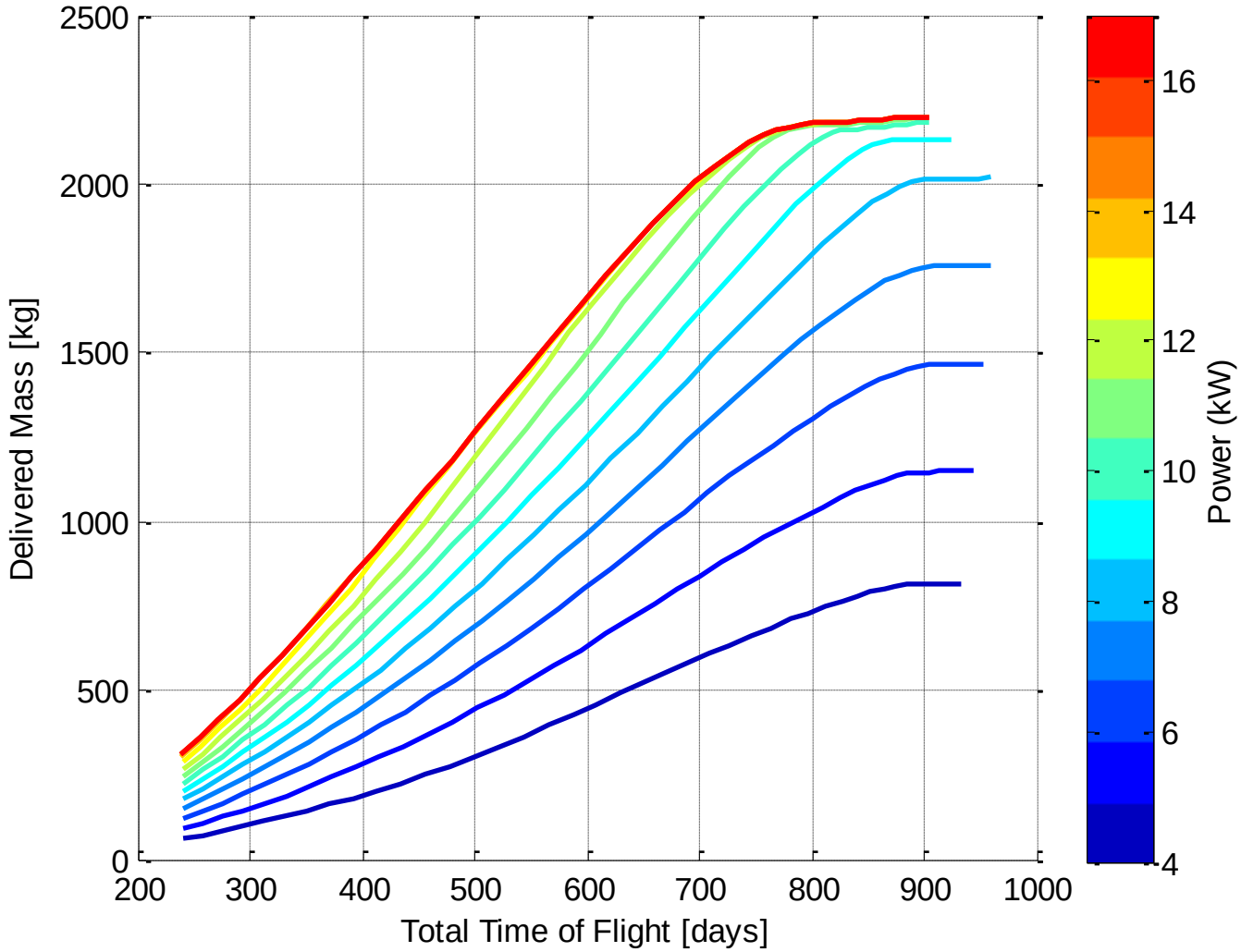
Outbound Trajectory (to Mars)

- Interplanetary flight time and solar array power (at 1 AU) are parametrically varied
- Spiral durations computed analytically

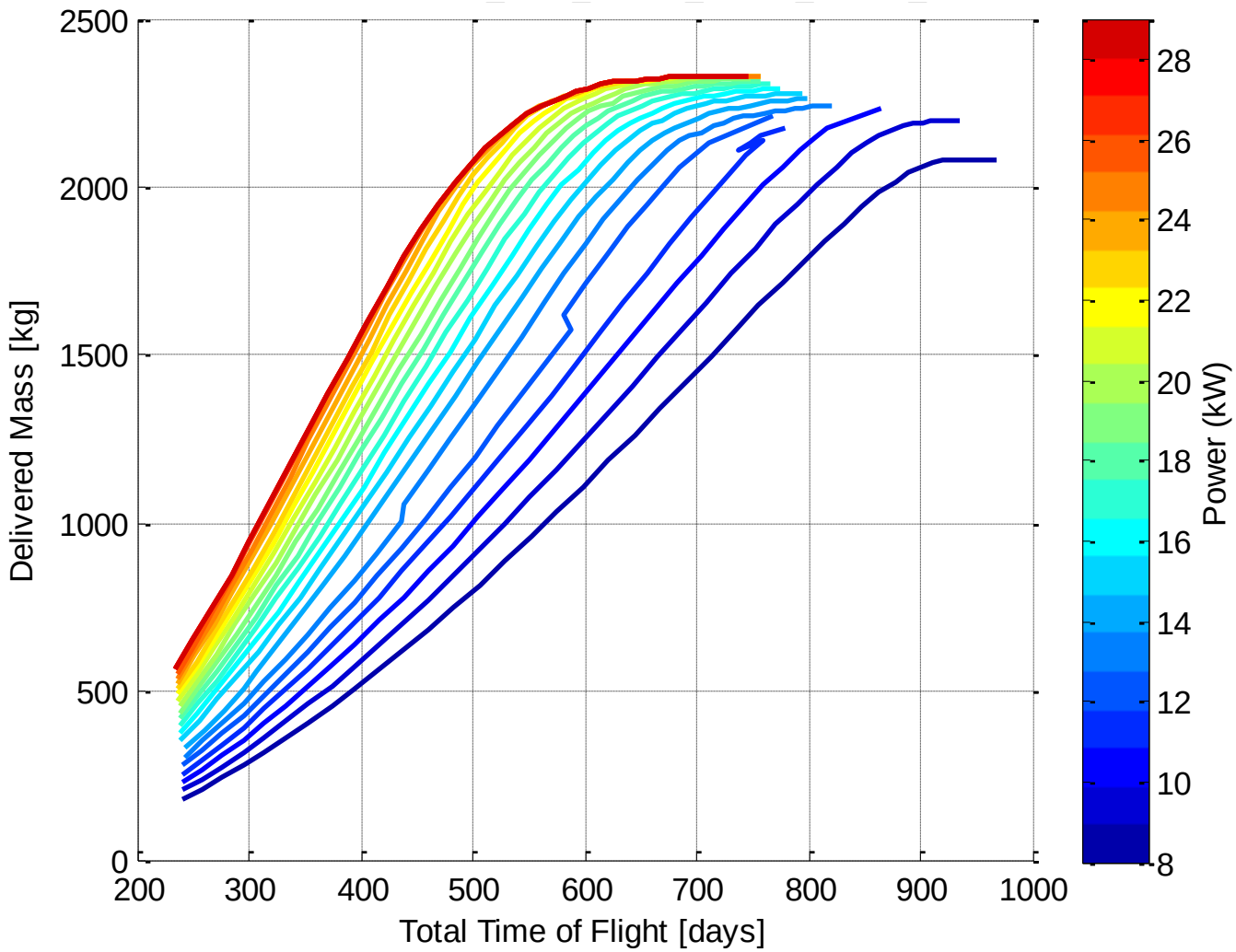


- Optimization variables
  - Launch & arrival dates
  - Launch C_3
  - Launch mass (tied to C_3 per the LV parametric model)
  - Thrust vector magnitudes (subject to available power limitations) and directions
- MALTO maximizes mass delivered to Mars

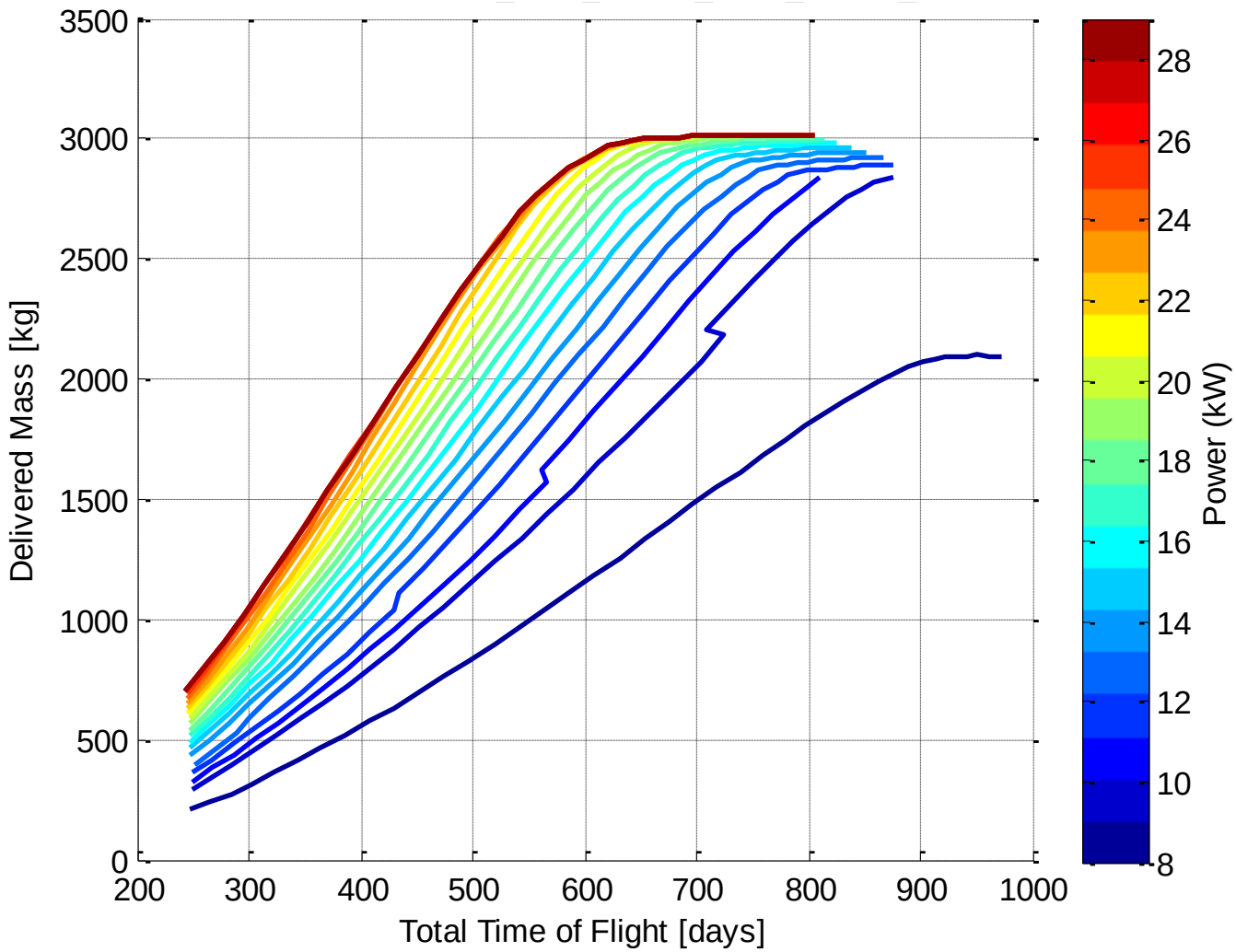
Earth → Mars – Falcon 9, 1 Engine



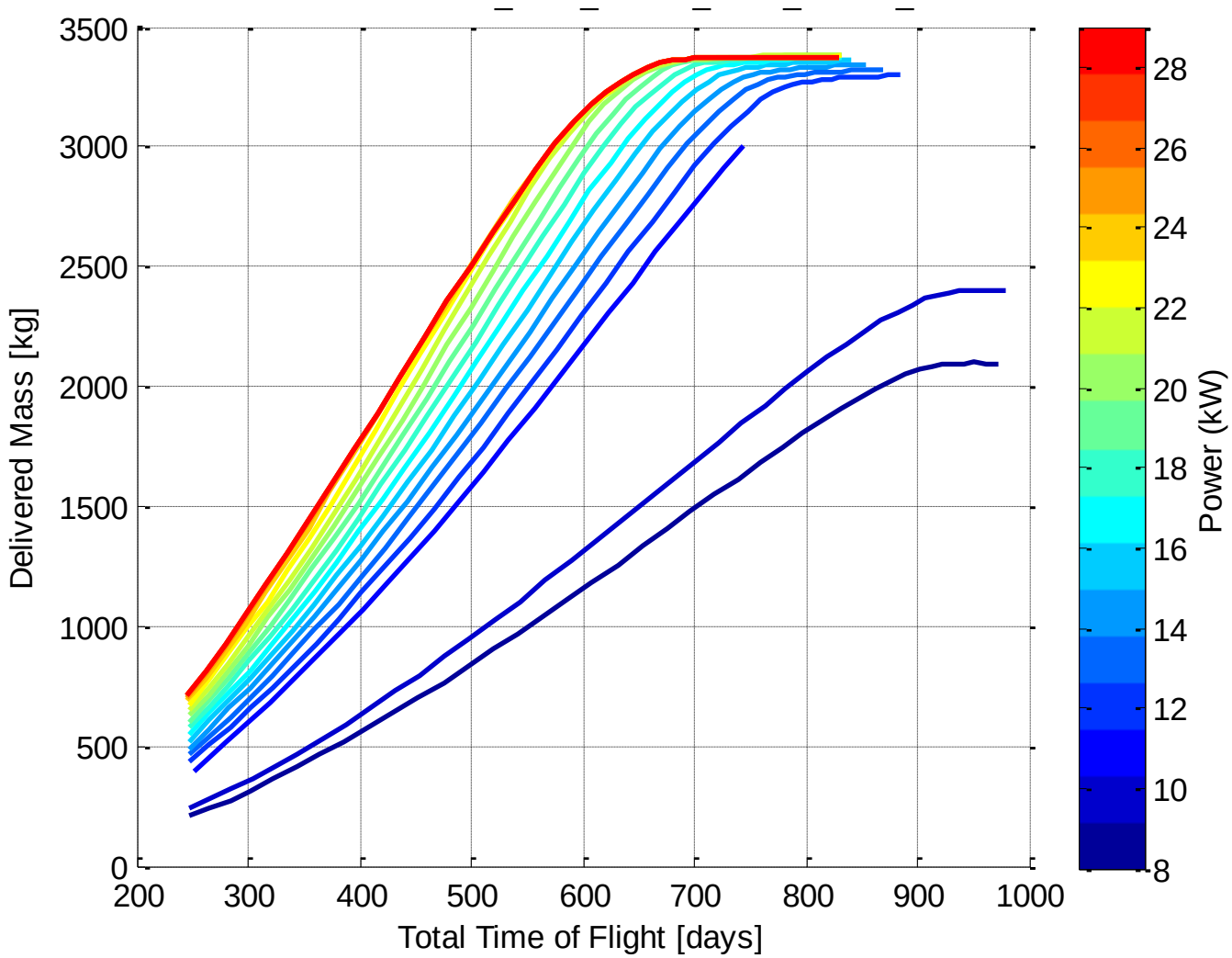
Earth → Mars – Falcon 9, 2 Engines



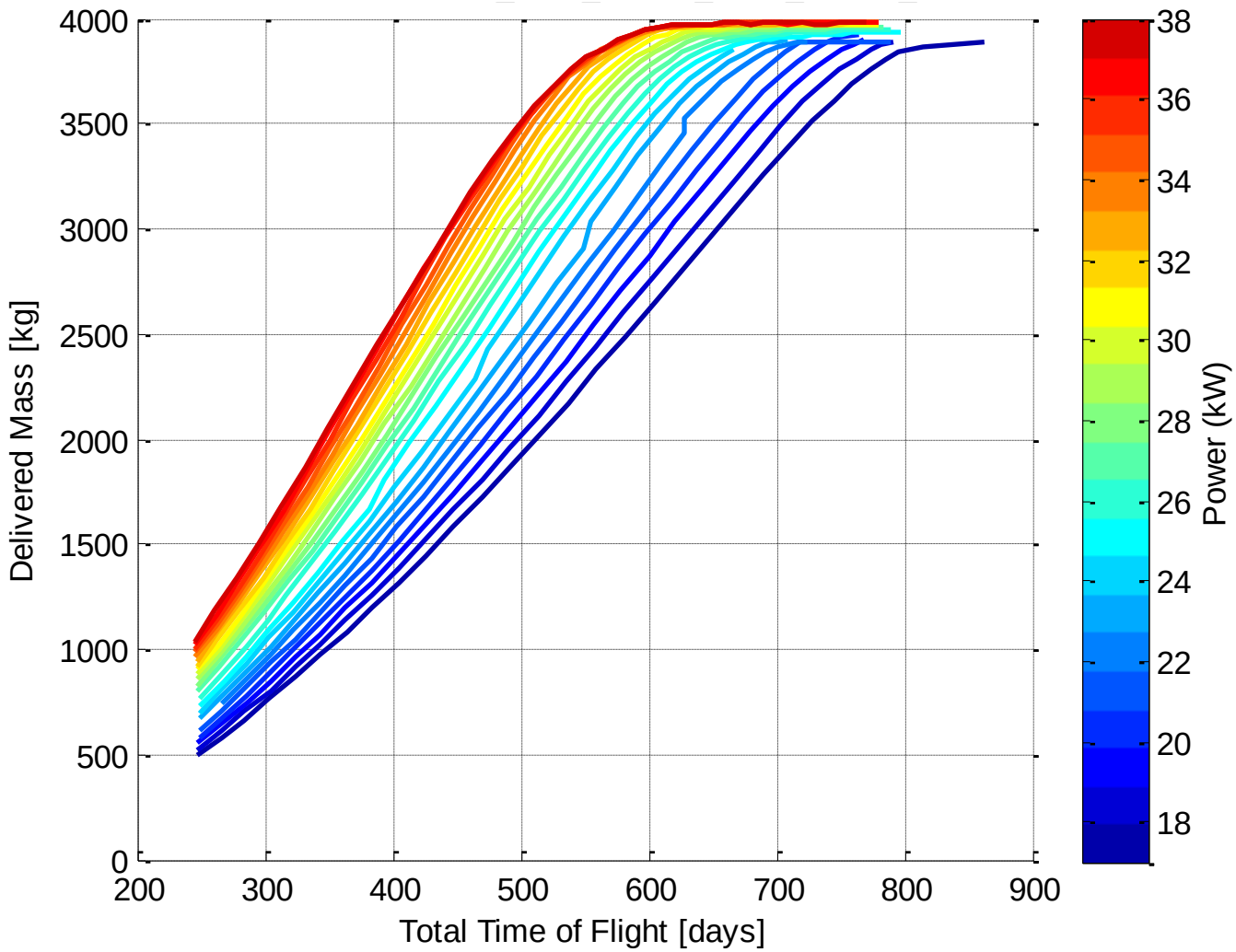
Earth → Mars – Atlas V 421, 2 Engines



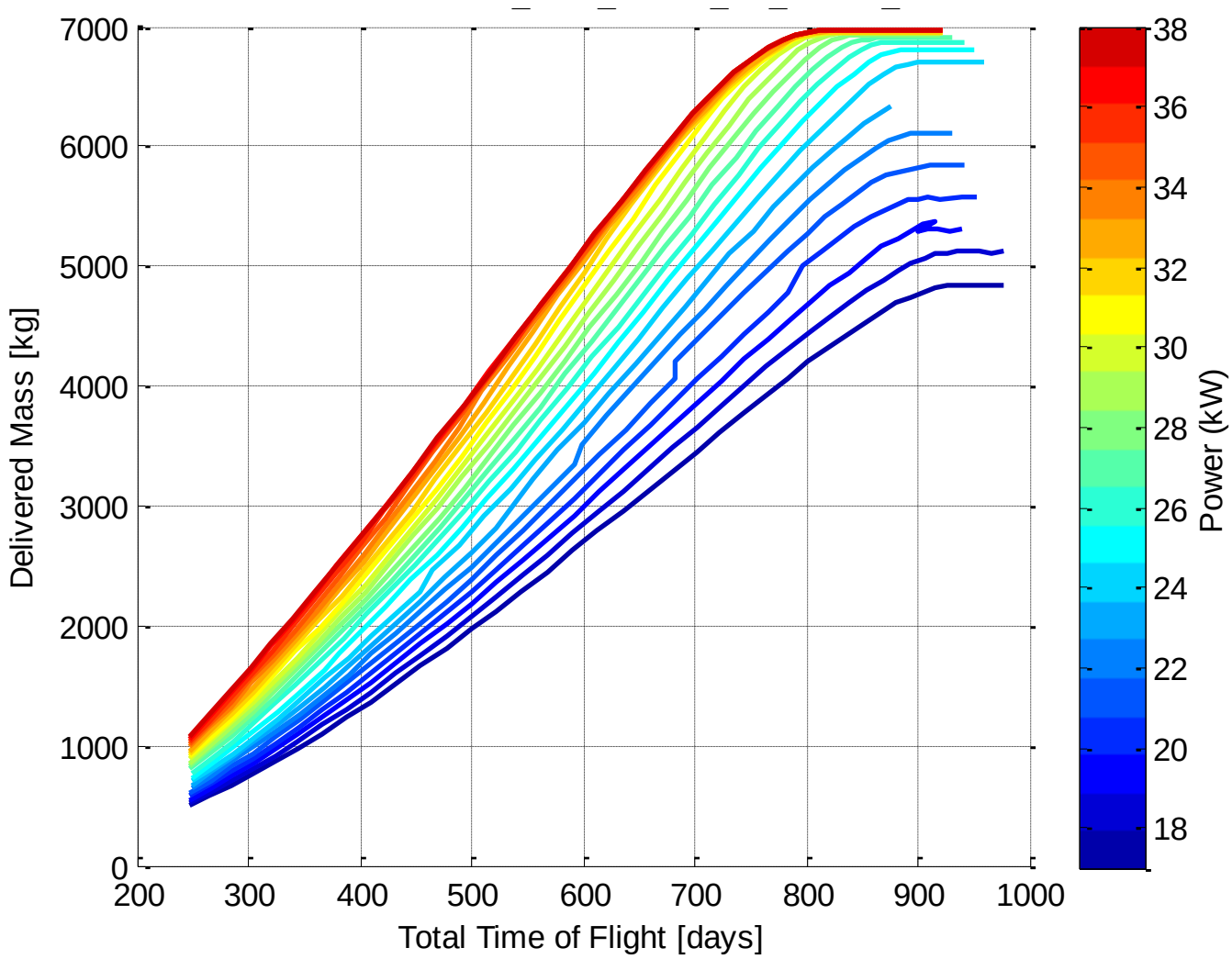
Earth → Mars – Atlas V 431, 2 Engines



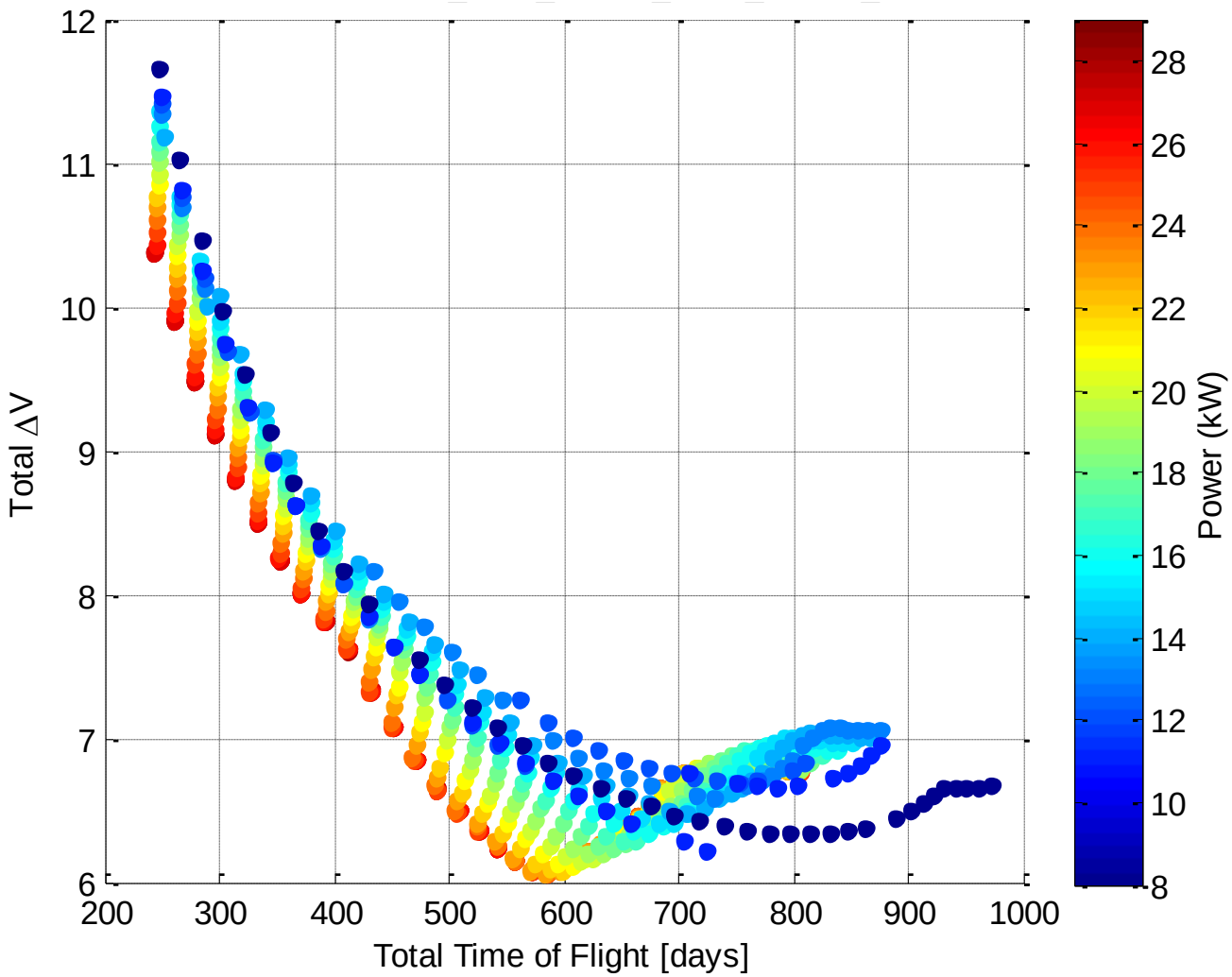
Earth → Mars – Atlas V 551, 3 Engines



Earth → Mars – Falcon Heavy, 3 Engines



Total ΔV

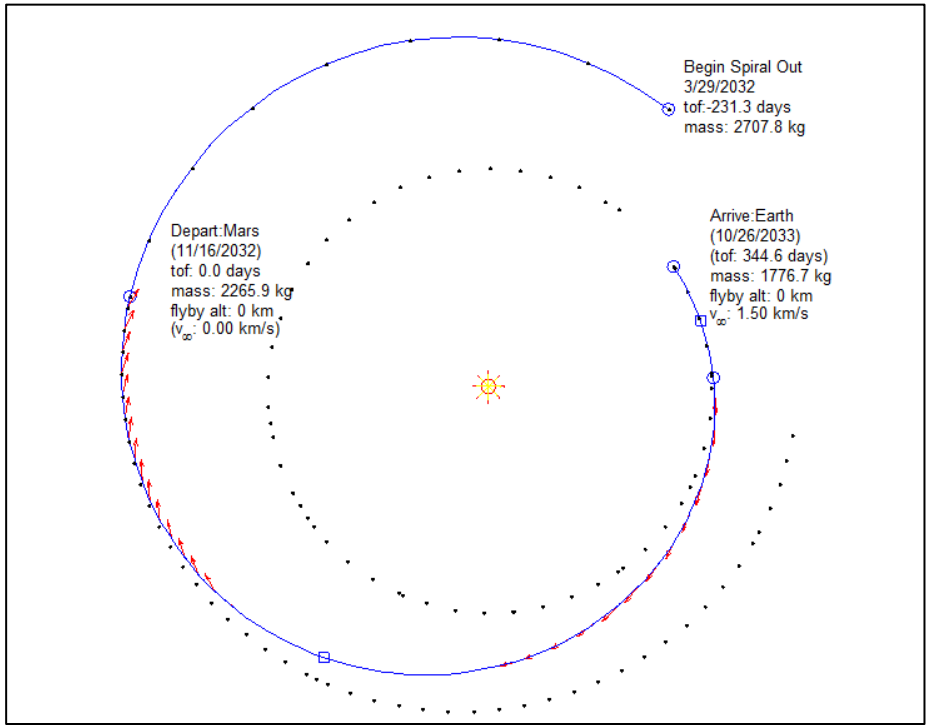


Atlas V 421, 2 Engines

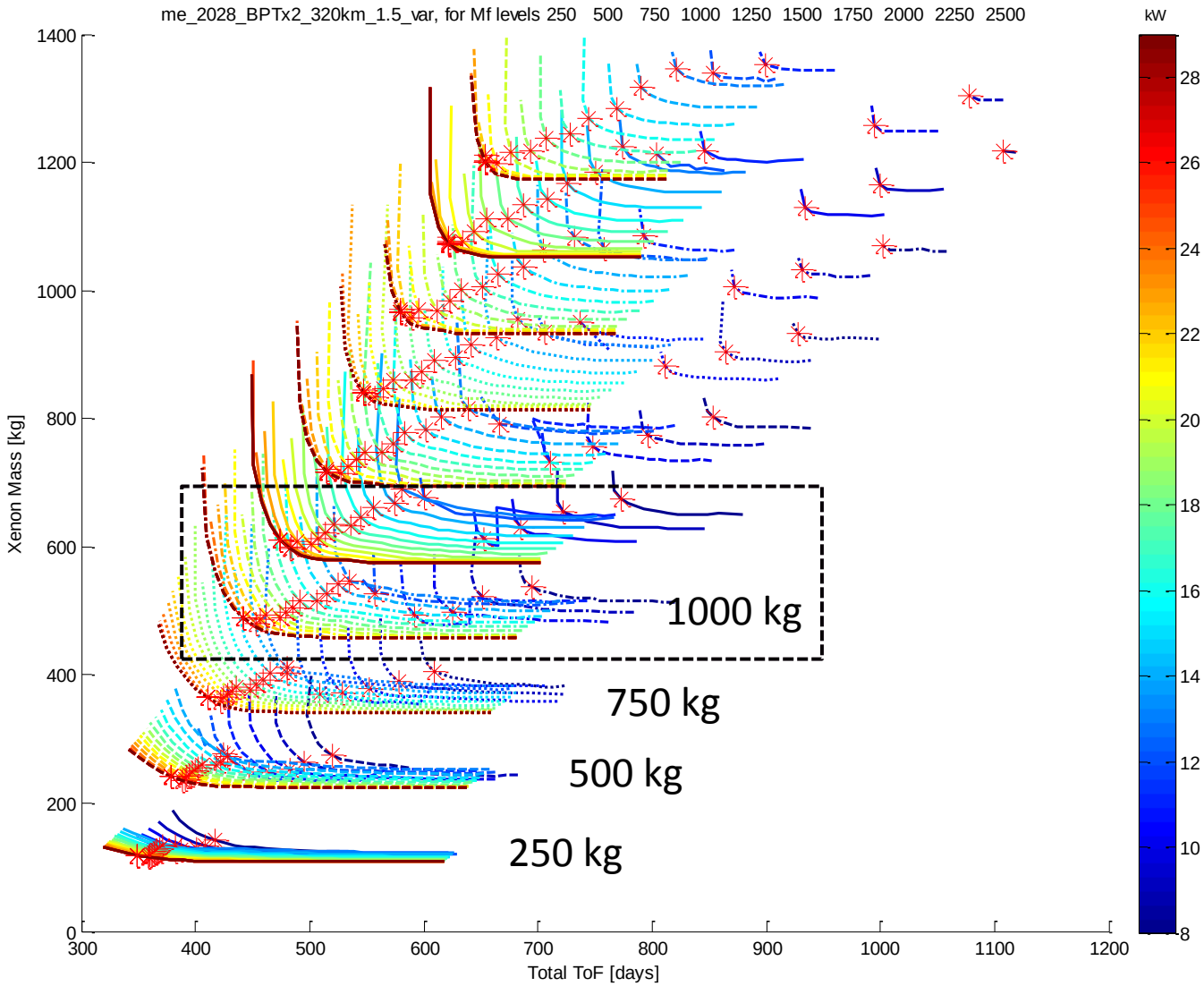
Inbound Trajectory (to Earth)

- Departing Mars, the spacecraft first spirals up then leaves with C_3=0
- Departure mass not tied to departure C_3 (no launch vehicle)
- Opted to fix the mass at Earth arrival to 250 – 2500 kg at 250 kg intervals
- Parametrically vary power and time-of-flight for each mass
- MALTO minimizes interplanetary propellant mass

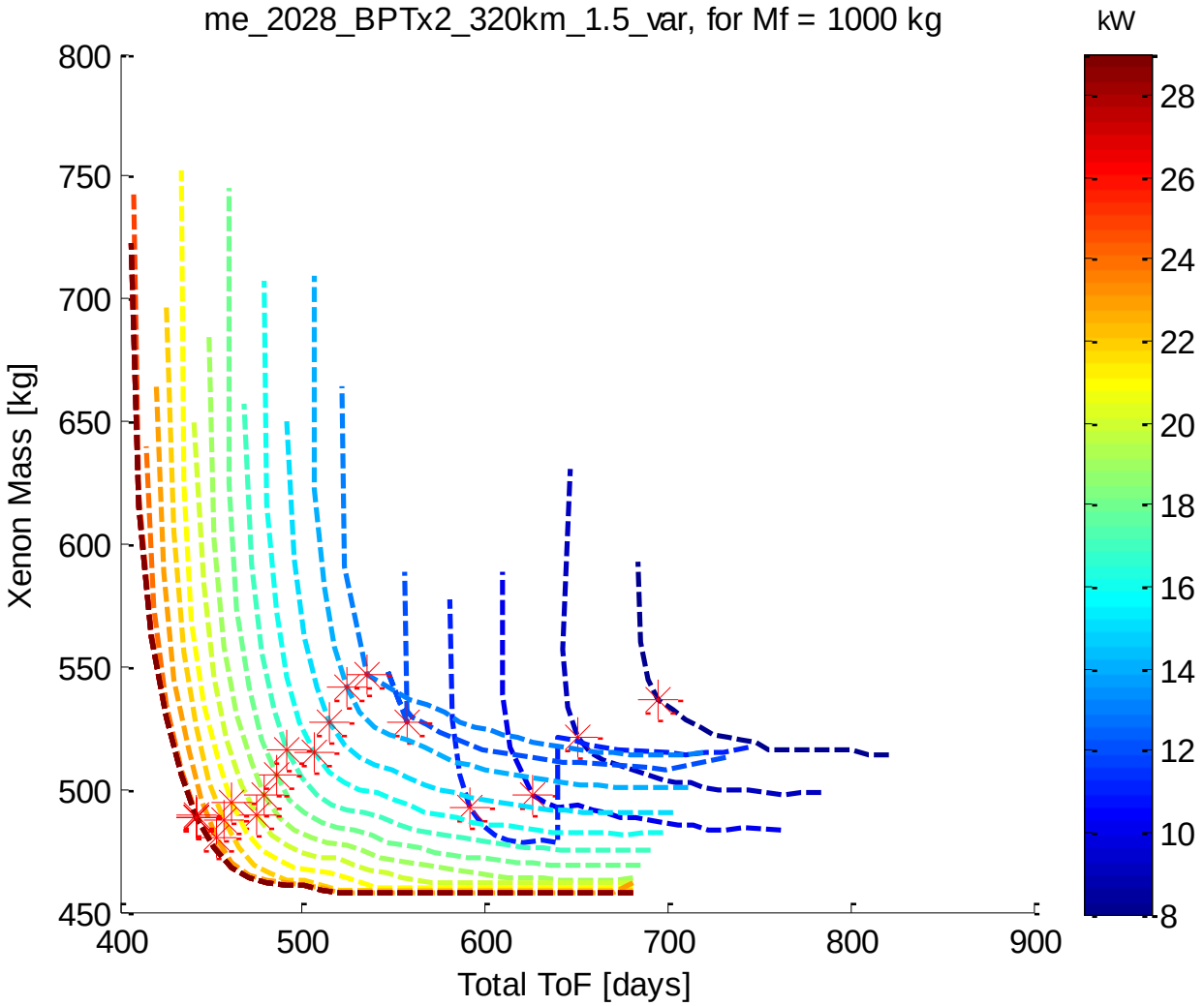
- Two Earth arrival V_∞ limits:
  - 1.5 km/s: 2 options
    - Lower velocity direct entry
    - Use lunar flybys to capture into a long-term stable orbit
  - 4.5 km/s: direct entry (future)



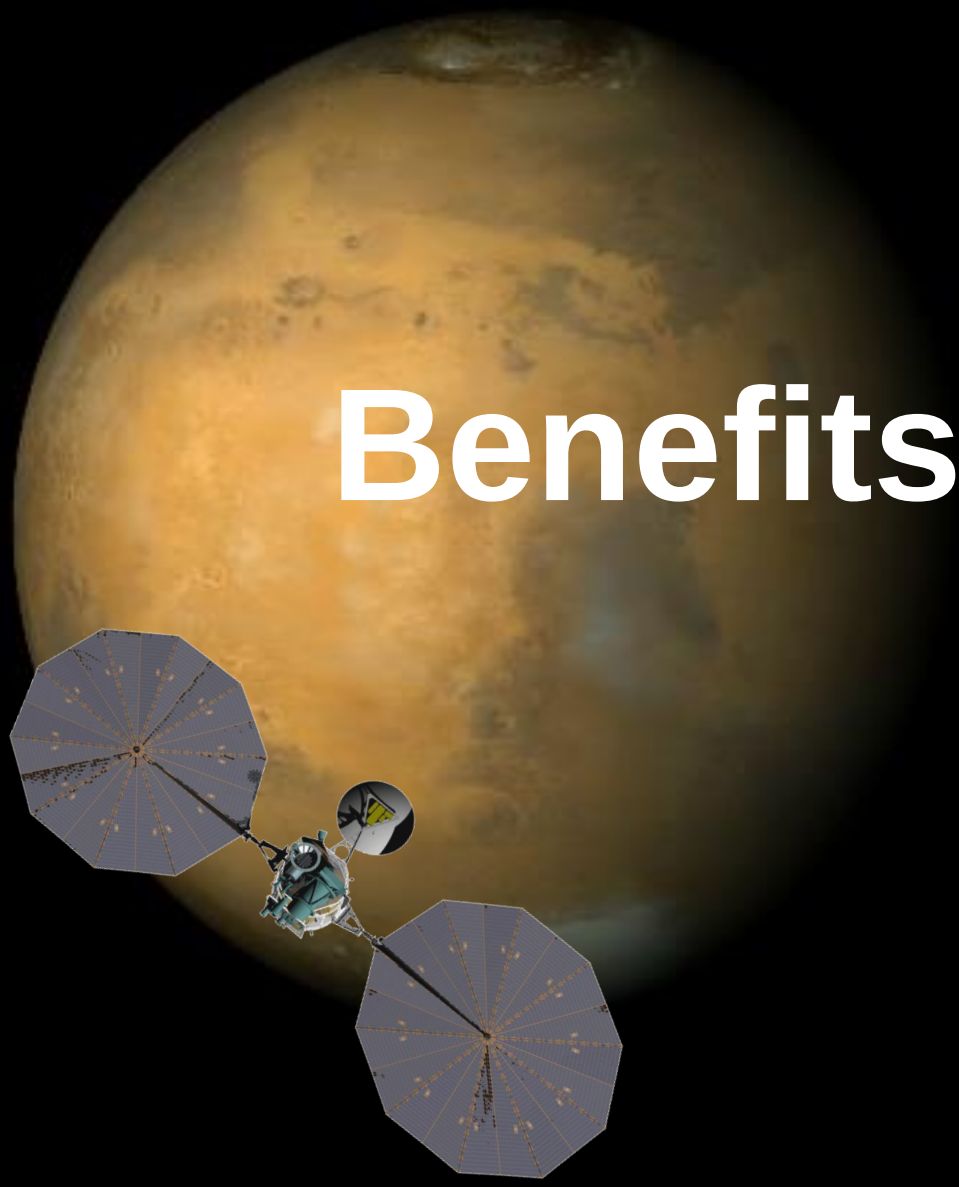
Mars → Earth Output



Mars → Earth – 1000 kg

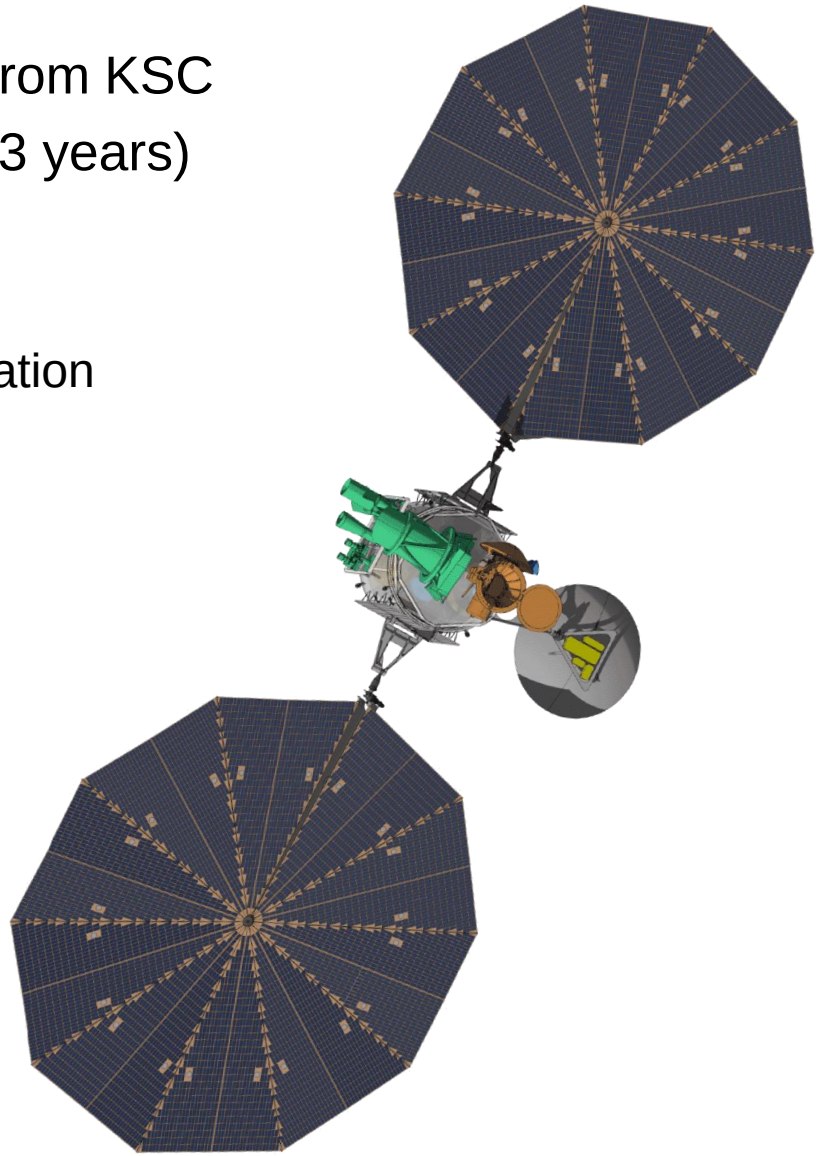


Benefits of SEP



Spacecraft Concept Overview

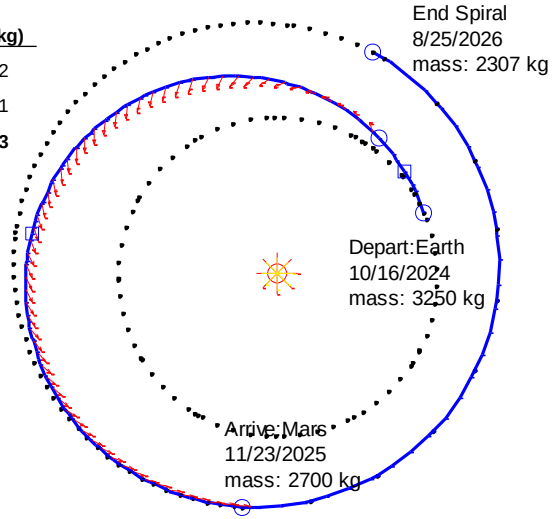
- Launch October 2024 on Atlas V421 from KSC
- Mission life of 9 years (design life of 13 years)
- Three-axis stabilization
  - Reaction wheels
  - Hydrazine thrusters for wheel desaturation
- SEP propulsion
  - Baseline 2+1 BPT-4000 thrusters
- Powered by ~65 m^2 solar array
  - Baseline 17.5 kW BOL @ 1 AU
- 2-m HGA with 200 W transmitter
- Design radiation dose of 25 krad
- Dual-string cold redundancy
- Planetary Protection Category III/V
- Mission risk class A



Mission Design (Reference Case)

Earth to Mars Trajectory (Outbound)

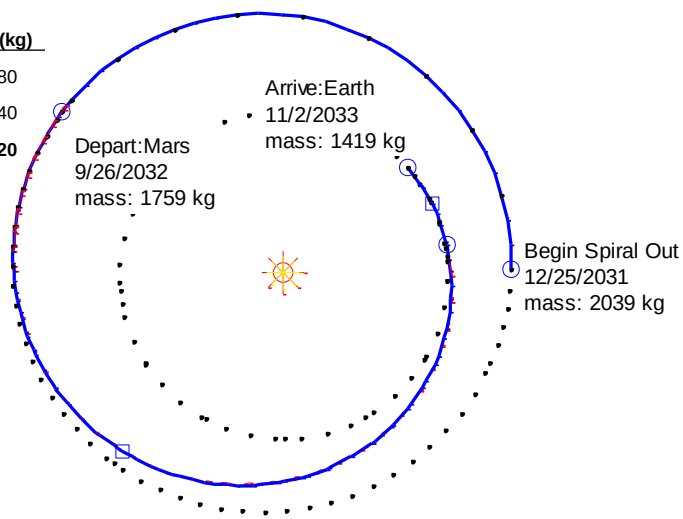
Leg	ΔV (km/s)	Xe (kg)
Helio	3.5	552
Spiral	2.8	391
	6.3	**943**



- Depart Earth: October 2024
- Atlas V421
  - Launch mass: 3250 kg
  - 25% Launch Vehicle Margin
    - Extra 700 kg delivered for 150 days TOF
  - C3: 17 km^2/s^2 (can be as low as 11)
- Total TOF: 680 days (1.9 years)
  - Heliocentric TOF: 400 d (14 mos.)
  - Spiral Duration: 280 d (8 mos.)
  - 30-day check-out period post launch

Mars to Earth Trajectory (Inbound)

Leg	ΔV (km/s)	Xe (kg)
Spiral	2.6	280
Helio	4.2	340
	6.8	**620**

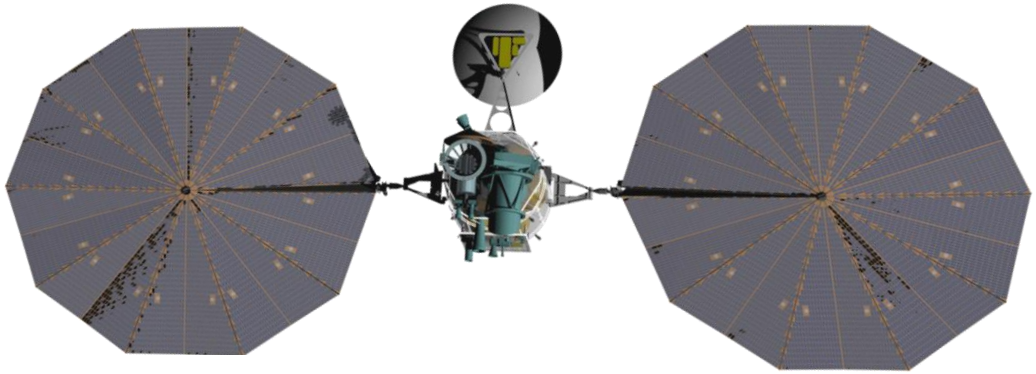


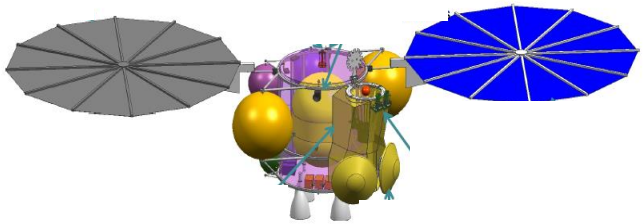
- Arrive at Earth: November 2033 (9 years)
- In Low Mars Orbit: 5.3 years
- Begin spiral out: December 2031
- Total TOF: 680 days (1.9 years)
  - Heliocentric TOF: 400 d (14 mos.)
  - Spiral Duration: 280 d (8 mos.)
  - 30-day no-burn period pre-Earth arrival
- Arrival V_∞: 1.5 km/s

SRO Chemical vs SEP comparison

Masses		
	SEP	Chem
Total	**2940**	**3150**
Propellant	**1448**	**2036**
Inbound	415	911
At Mars	28	253
Outbound	837	872
Margin Xe	126	*included
ACS	43	*included
Bus	**1492**	**1115**
Payload	300	300
Margin	290	196
ADCS	52	68
CDHS	19	19
Telecom	35	35
Structures	266	206
Thermal	41	31
Propulsion	170	127
Power	274	100
Harness	45	33

SEP has more dry mass but less fuel mass





Overall Mission durations are comparable (9 years), but SEP spends 600 less days in Mars orbit

Timeline				
Event	SEP		Chem	
Launch	10/16/2024		9/24/2024	
Arrive	11/23/2025	403 days	8/22/2025	332 days
LMO	8/25/2026	275 days	2/18/2026	180 days
Depart	12/25/2031	**1948 days**	1/18/2033	**2526 days**
End Spiral	9/26/2032	276 days	-	-
Earth	11/2/2033	402 days	8/30/2033	224 days

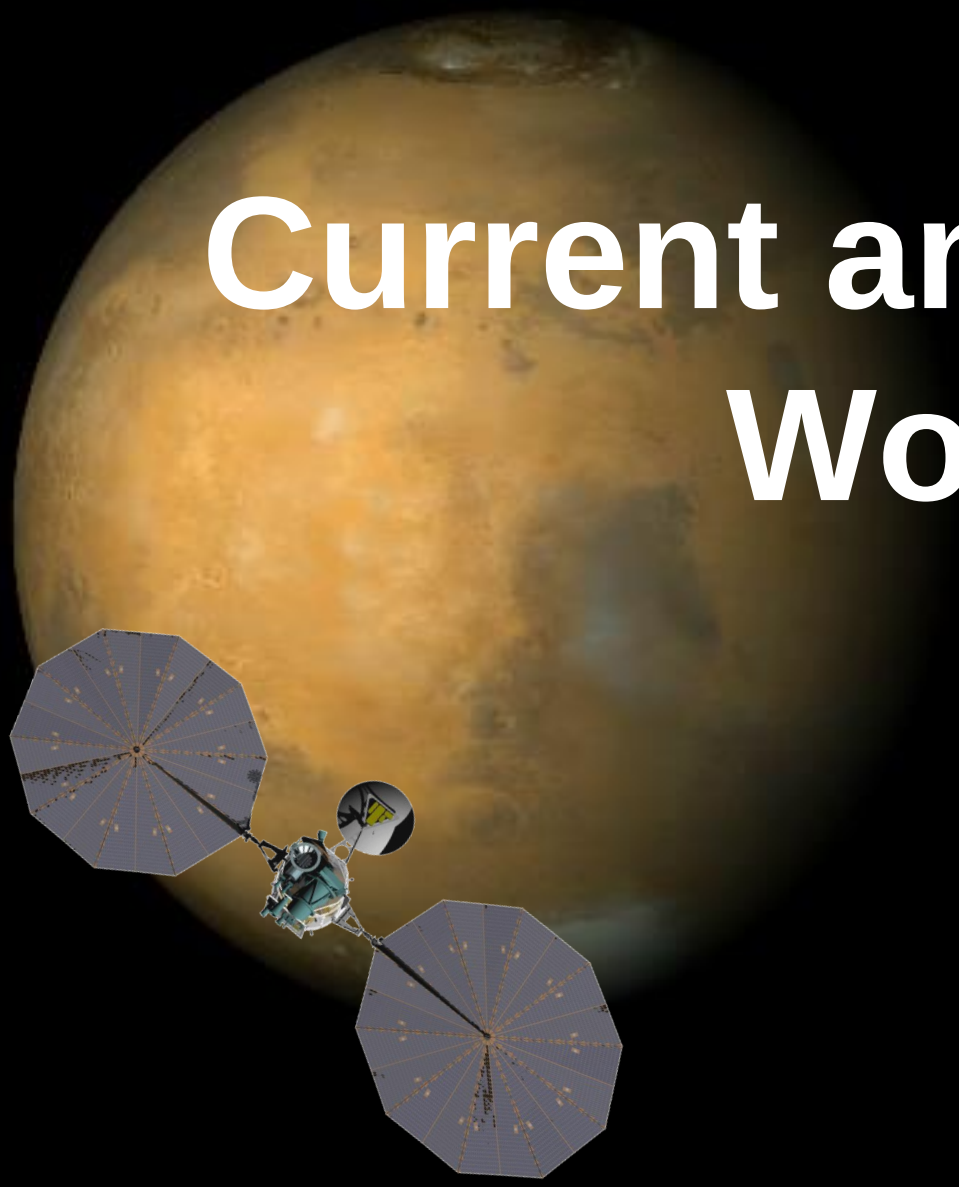
ΔV		
ΔV Budget	SEP	Chem
To Mars	3325	30
Capture	2968	983
Mission	223	350
Return	6340	2133
Total	**12856**	**3497**

SEP requires 4x the ΔV but has 6x the Isp

Pros/Cons of SEP

- Pros
  - Extra power for science
  - Possible Phobos/Deimos flybys or rendezvous
  - Flexible timeline – launch periods, phasing, margins
  - No critical events at Mars
  - Earth V_∞ = 1.5 – allows late decision to DRO orbit
- Cons
  - Requires equivalent mass, due to:
    - Extra mass for prop. system and power (450 kg vs. 230 kg)
    - Quadruple the mission ΔV
  - Longer transfer times → 600 less days at Mars
  - Must leave Mars earlier (probably can't do 2030 return)
  - Extra cost?

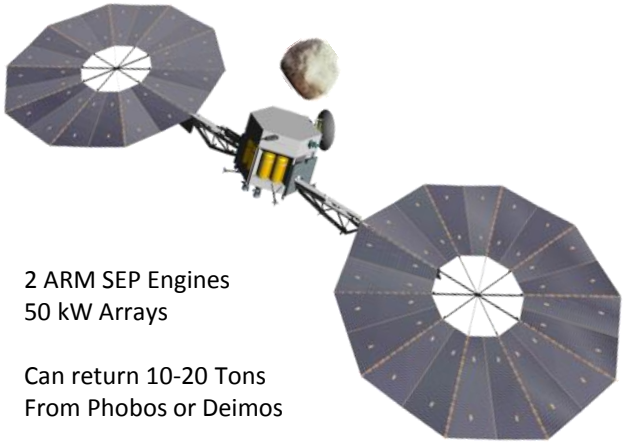
Current and Future Work



Mission Concept Cases

- Deimos or Phobos Boulder Return
  - "Land" in micro-g, grab a boulder and return to Earth

Falcon Heavy

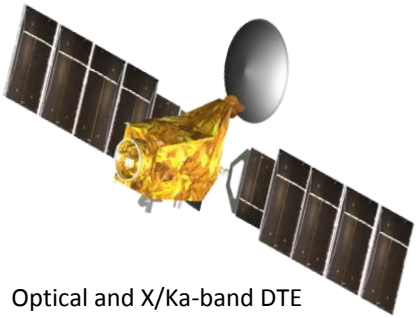


2 ARM SEP Engines
50 kW Arrays

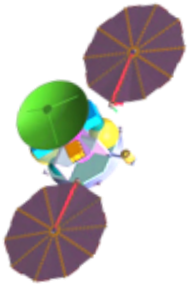
Can return 10-20 Tons
From Phobos or Deimos

- Large telecom orbiter drops off small science orbiter
  - Drop off in LMO, return to ASO

Falcon 9



Optical and X/Ka-band DTE
X-band Relay

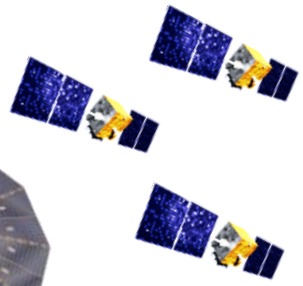


Odyssey-class
Science/Relay

- MSR Orbiter drops off multiple Telecom orbiters at ASO
  - Also performs science at Phobos, Deimos, and LMO

Atlas V 551

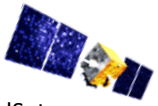
Sample Return
and MRO-Class
Science



TelSats
(X-band + Optical)

- Science orbiter drops off several daughter-craft
  - Landers at Phobos & Deimos
  - Telsat at ASO
  - Cubesats anywhere

Falcon 9



TelSat
(X-band + Optical)

Phobos/Deimos Landers

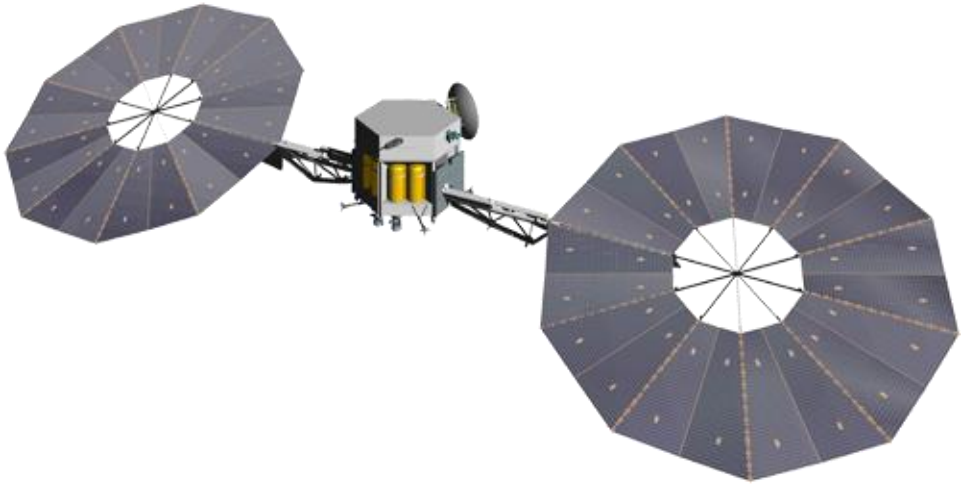
MRO-Class
Science/Relay
Orbiter

Near Term Studies

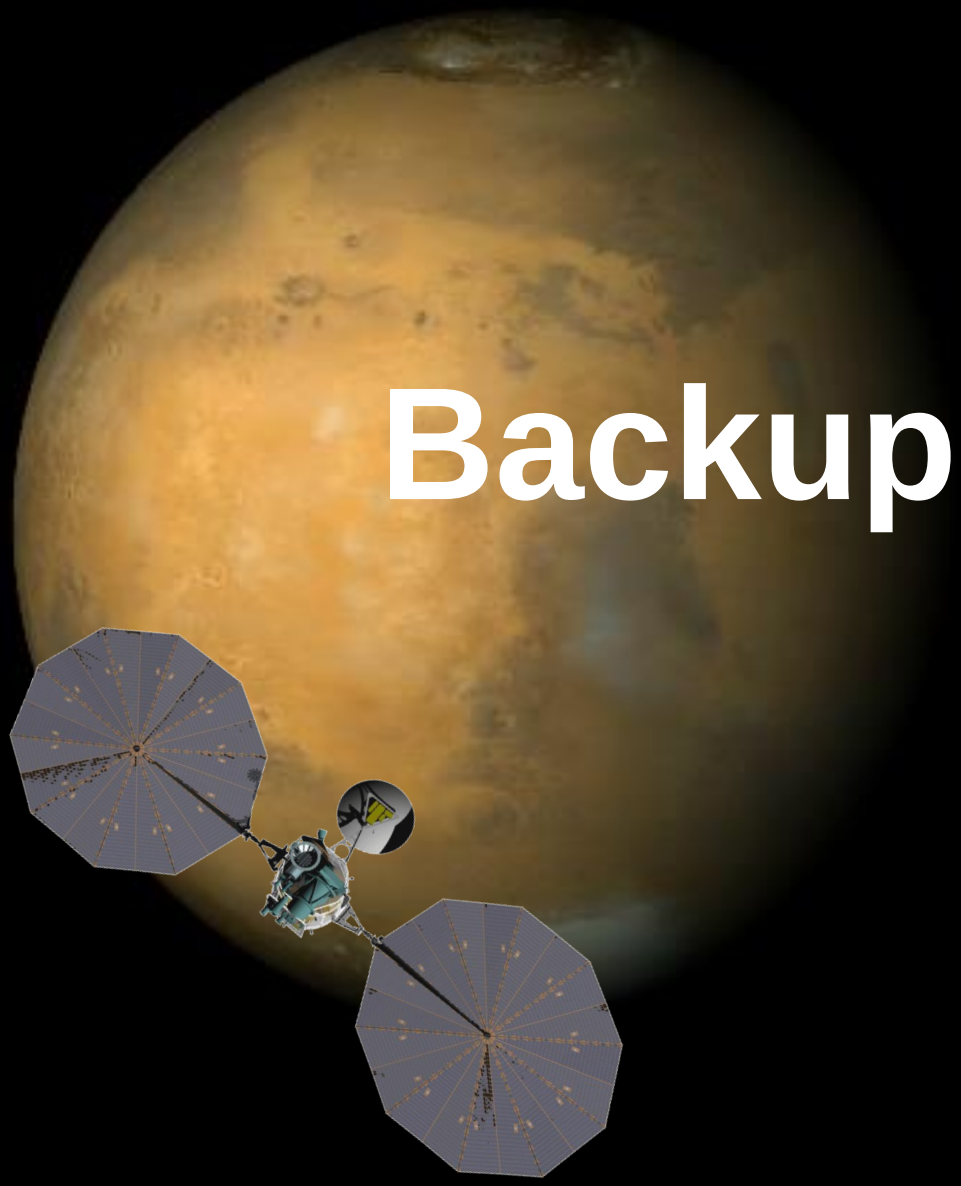
- MALTO trajectories
  - Additional launch vehicles, configurations
  - Additional thrusters and types (including NEXT, ARM)
  - “Porkchop Plots” for outbound and inbound departure/arrival conditions

- System Margin Strategies
  - Statistical methods of assessing interdependent margins

- Adapting model for multiple orbiter types (daughter craft, non-SRO orbiters)

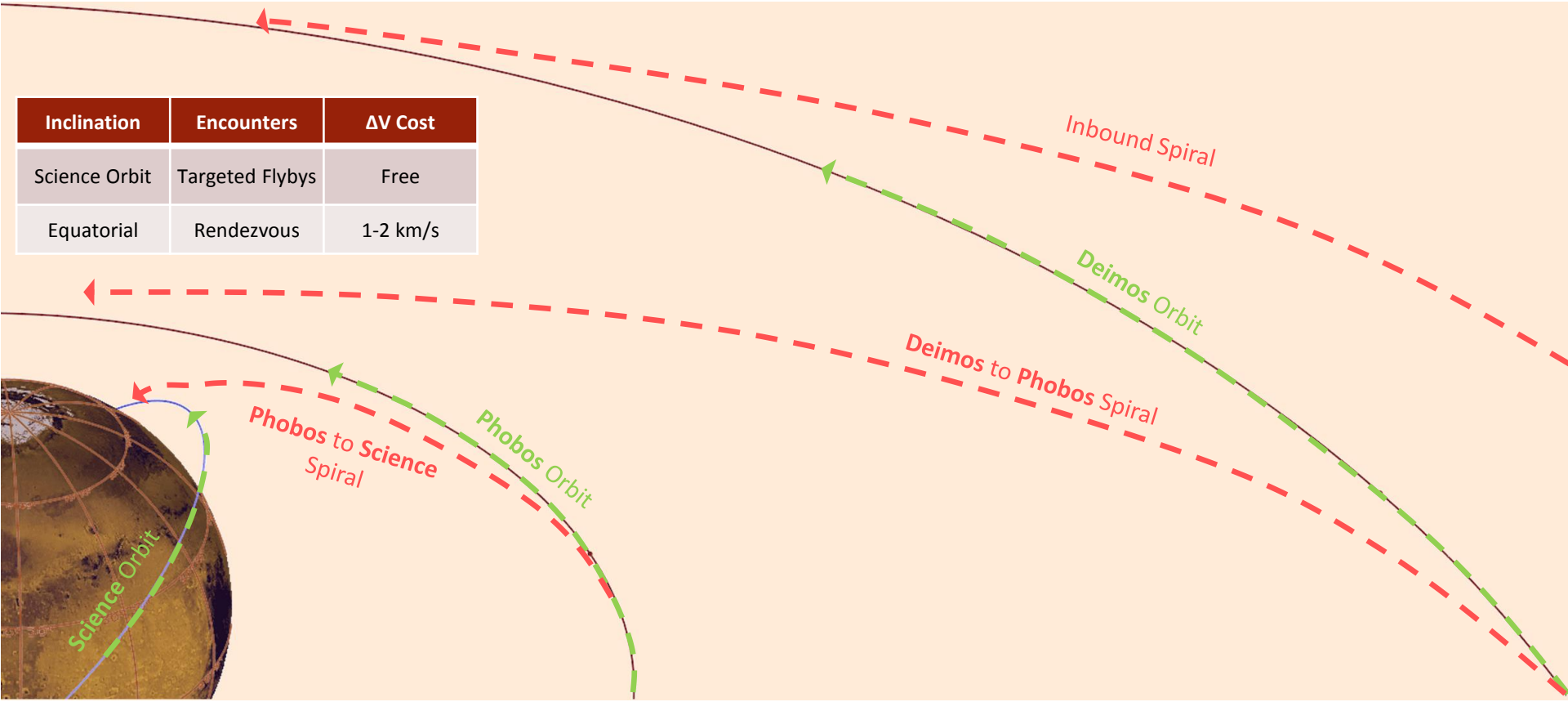


Backup Slides



Phobos and Deimos Science

Inclination	Encounters	ΔV Cost
Science Orbit	Targeted Flybys	Free
Equatorial	Rendezvous	1-2 km/s



	Science	Phobos	Deimos
Altitude	~300 km	6400 km	20400 km

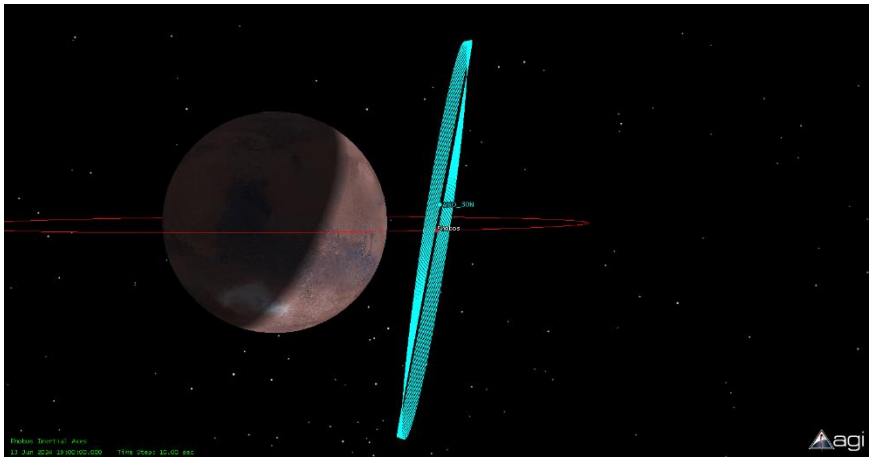
Opportunity to target multiple moon fly-bys during inbound spirals

Credit: Sean Lawlor and Anirudh Tadanki

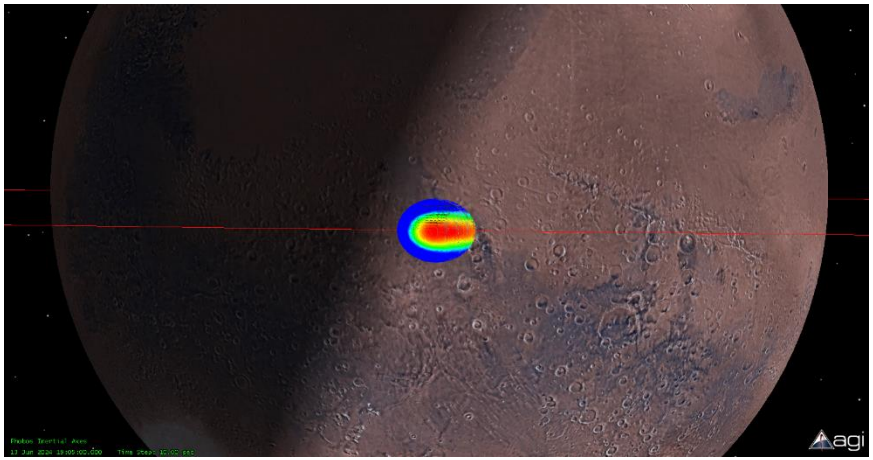
Pre-Decisional: For planning and discussion purposes only.

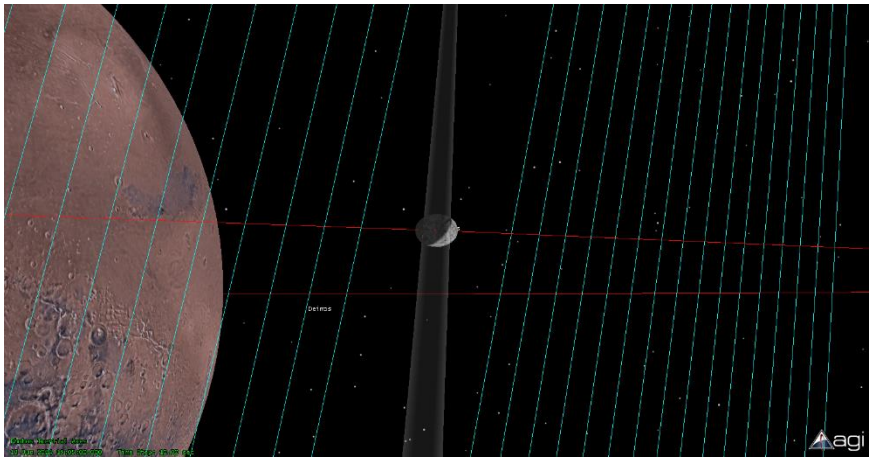
Phobos Coverage

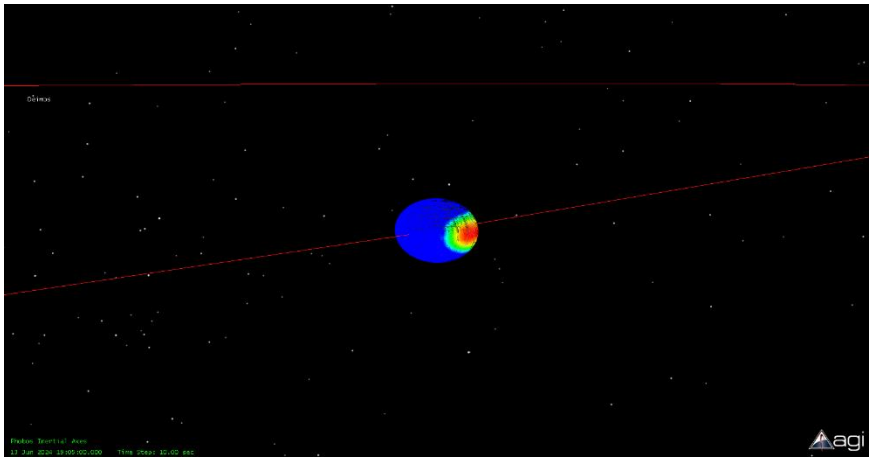
Orbit



Coverage



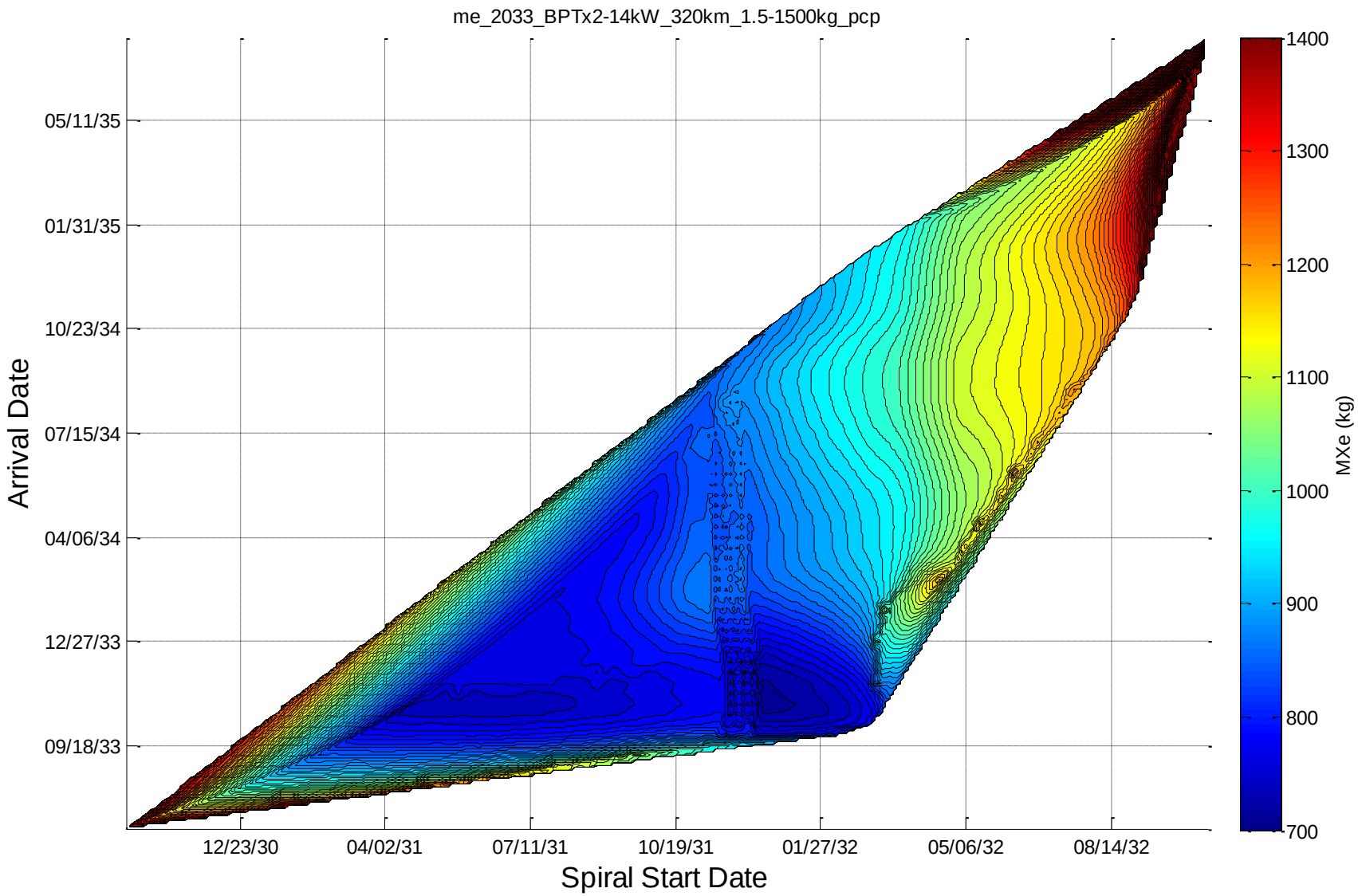




40 1,220 2,400

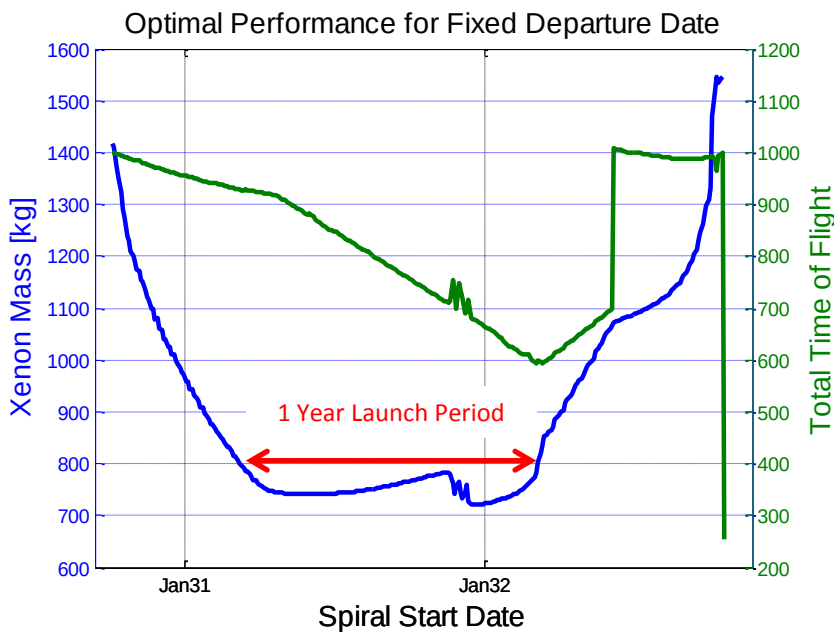
Total Time (sec)

SEP "Porkchop" Plot

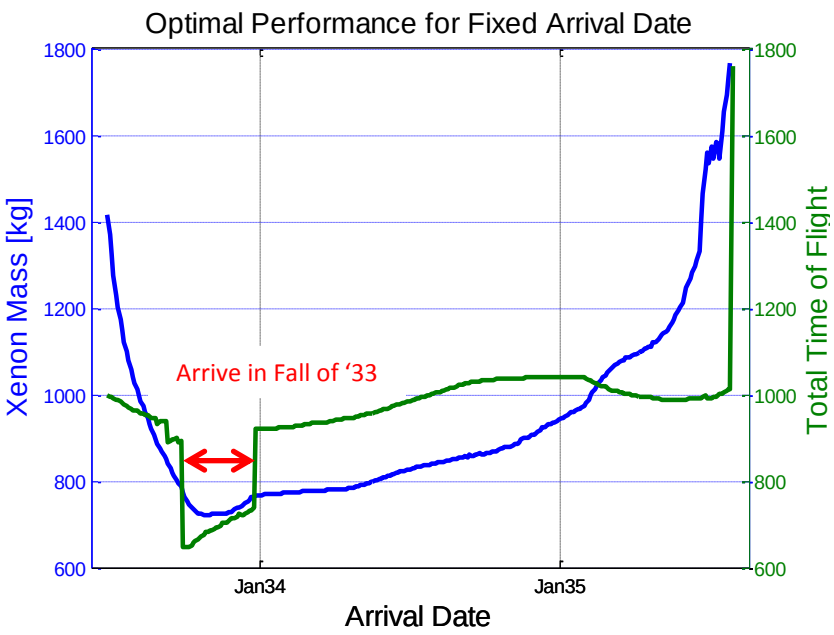


Launch Period Implications

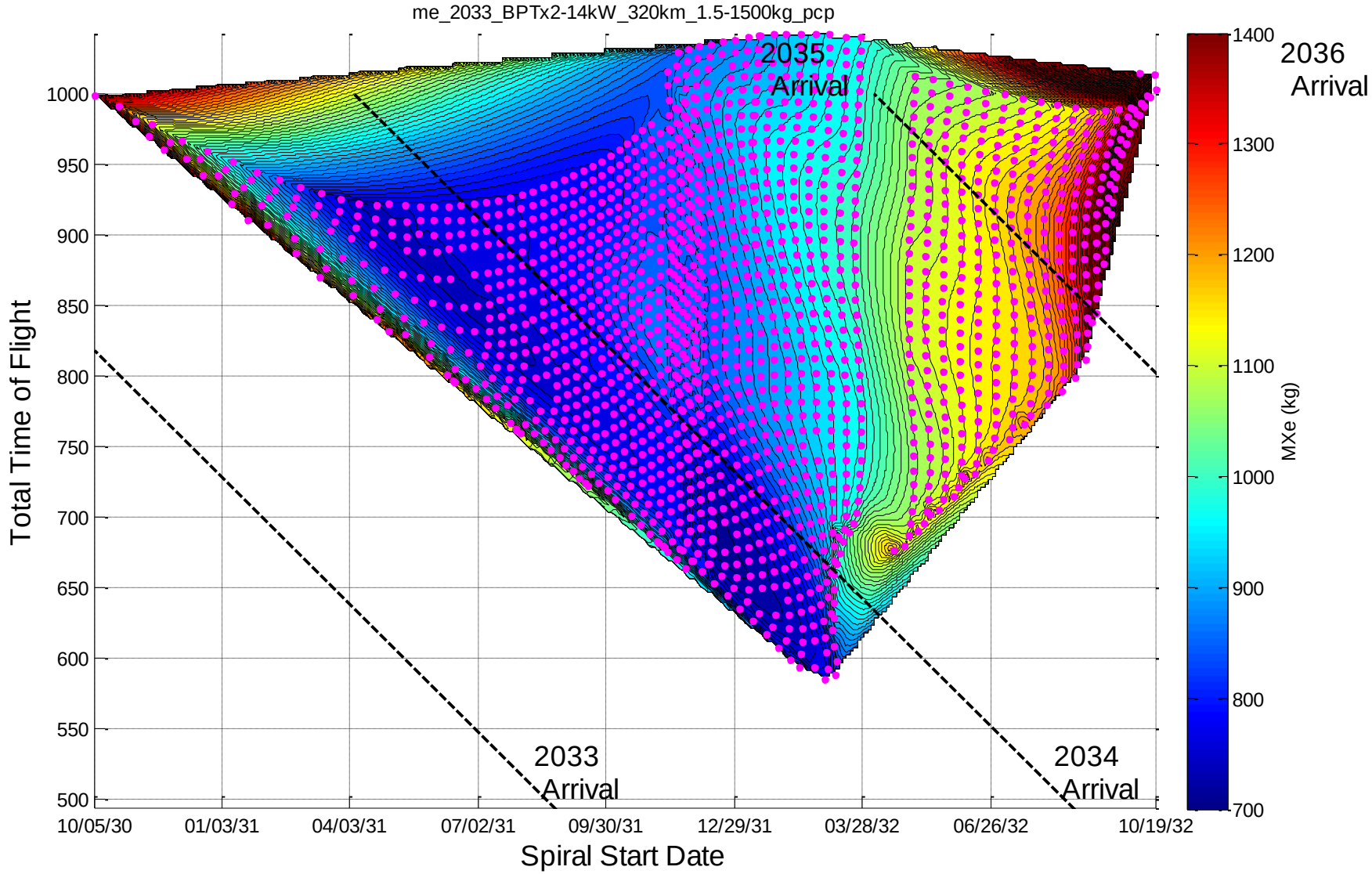
Best Departure Date



Best Arrival Date

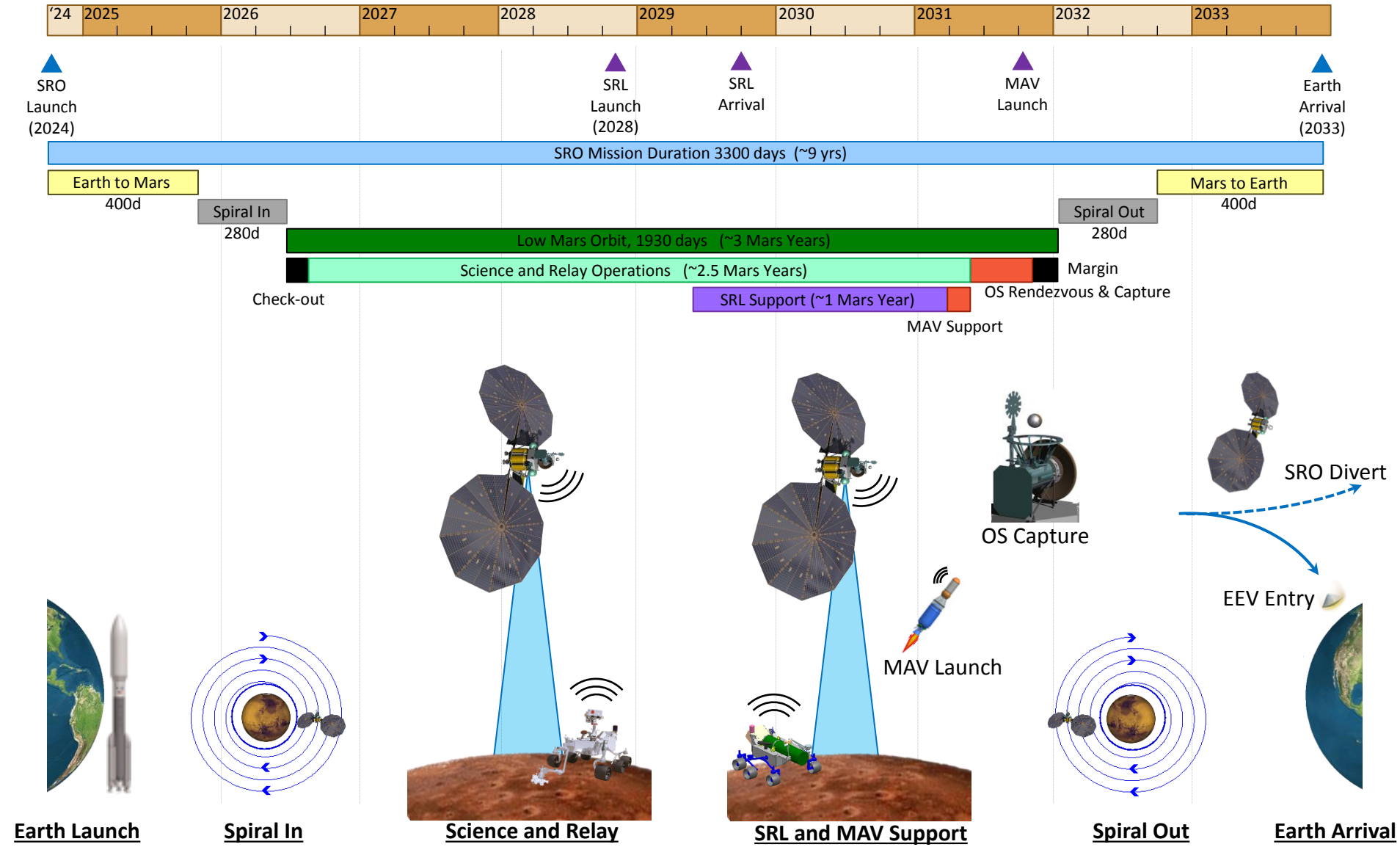
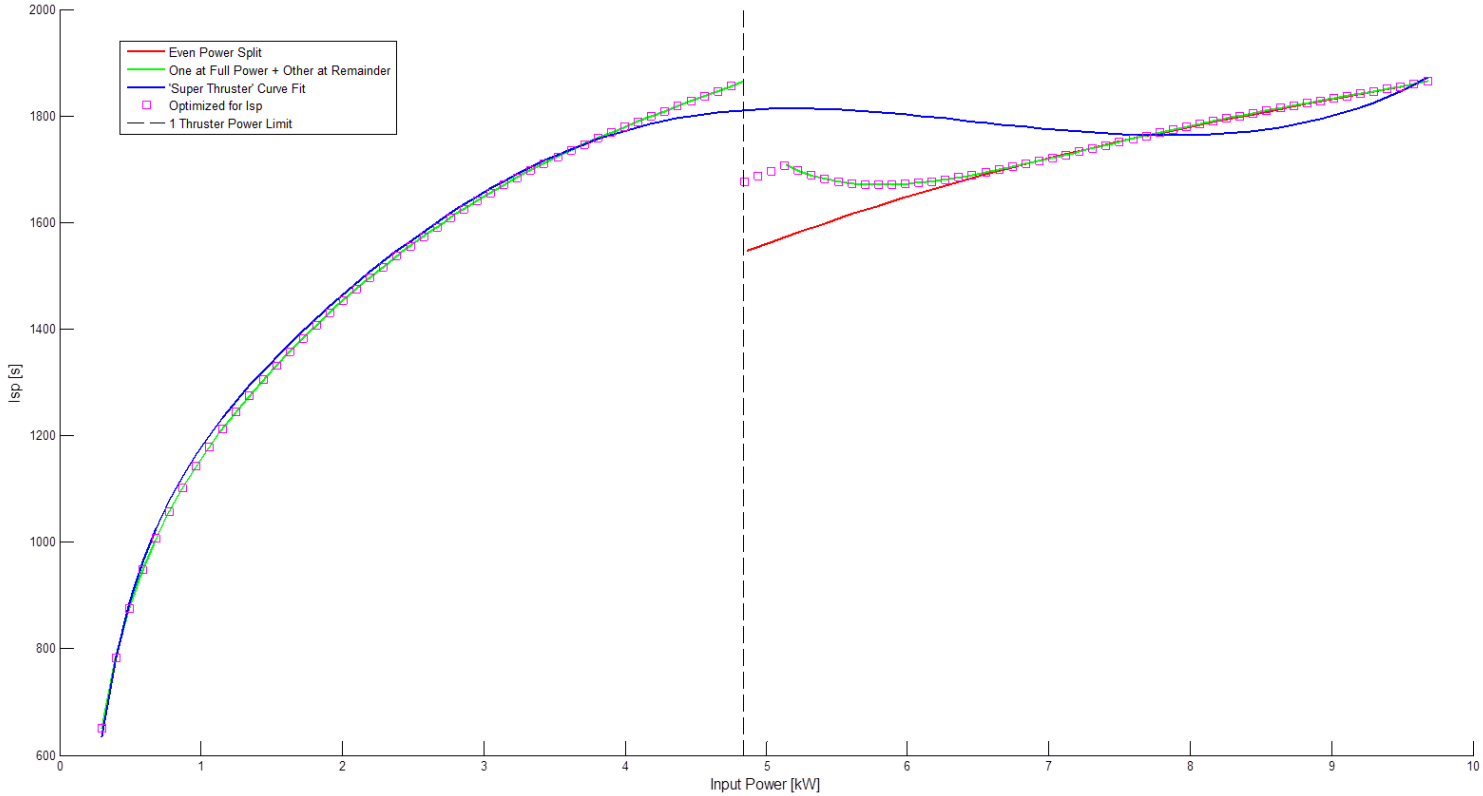


SEP "Porkchop" Plot (TOF)



SRO Reference Mission

Notional Timeline and Launch Dates



“Super Thruster” Model