18th Space Science Symposium

Conceptual Study of Mars Aerocapture Orbiter
火星エアロキャプチャオービタの概念検討

2018/1/10

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はじめに

■ 本文書の目的

- 本文書は，イプシロンロケット（増強型）を利用した小型ミッションとして，火星エアロキャプチャオービタの概念検討を実施したものである.

■ 適用文書

■ 参考文書

1. 藤田ほか,「イプシロンロケットによる火星着陸探査の可能性検討」,イプシロン搭載宇宙科学ミッション•シンポジウム, 宇宙科学研究所, 2014 年 1 月.
2. 藤田ほか,「将来の火星着陸探査に求められる輸送系技術と研究開発の現状」, 第 49 回 月•惑星シンポジウム, 宇宙科学研究所, 2016 年 7 月.
3. イプシロンロケットによる火星探査の可能性検討（技2016-00-20A）
4. エアロキャプチャ技術の研究 平成 29 年度 究計画書（技2016-00-39）
5. ロケットフェアリングを用いたエアロキャプチャシステムの初期検討（技2016-00-28B）
6. HTV-M と火星探査技術実証計画（提案）（技2017-00-10A）
7. フェアリング一利用火星エアロキャプチャのコリドー検索（技2017-02-01A）
8. 藤田ほか,「火星探査の新しい戦略と火星探査技術実証（提案）」,惑星科学会 2017 年秋季講演会, 大阪大学, 2017 年 9 月.
9. 藤田和央,「火星探査の現在, 過去, 未来」,第 2 回重力天体着陸シンポジウム, 宇宙科学研究所, 2017 年 2 月.

改訂記録

改訂記号	改訂内容	改訂日	改訂者
初版	技2017-02-06の検討内容をアップデート	2018/01/10	藤田和央

Purpose, Goal, & Objectives of Mars Aerocapture Orbiter

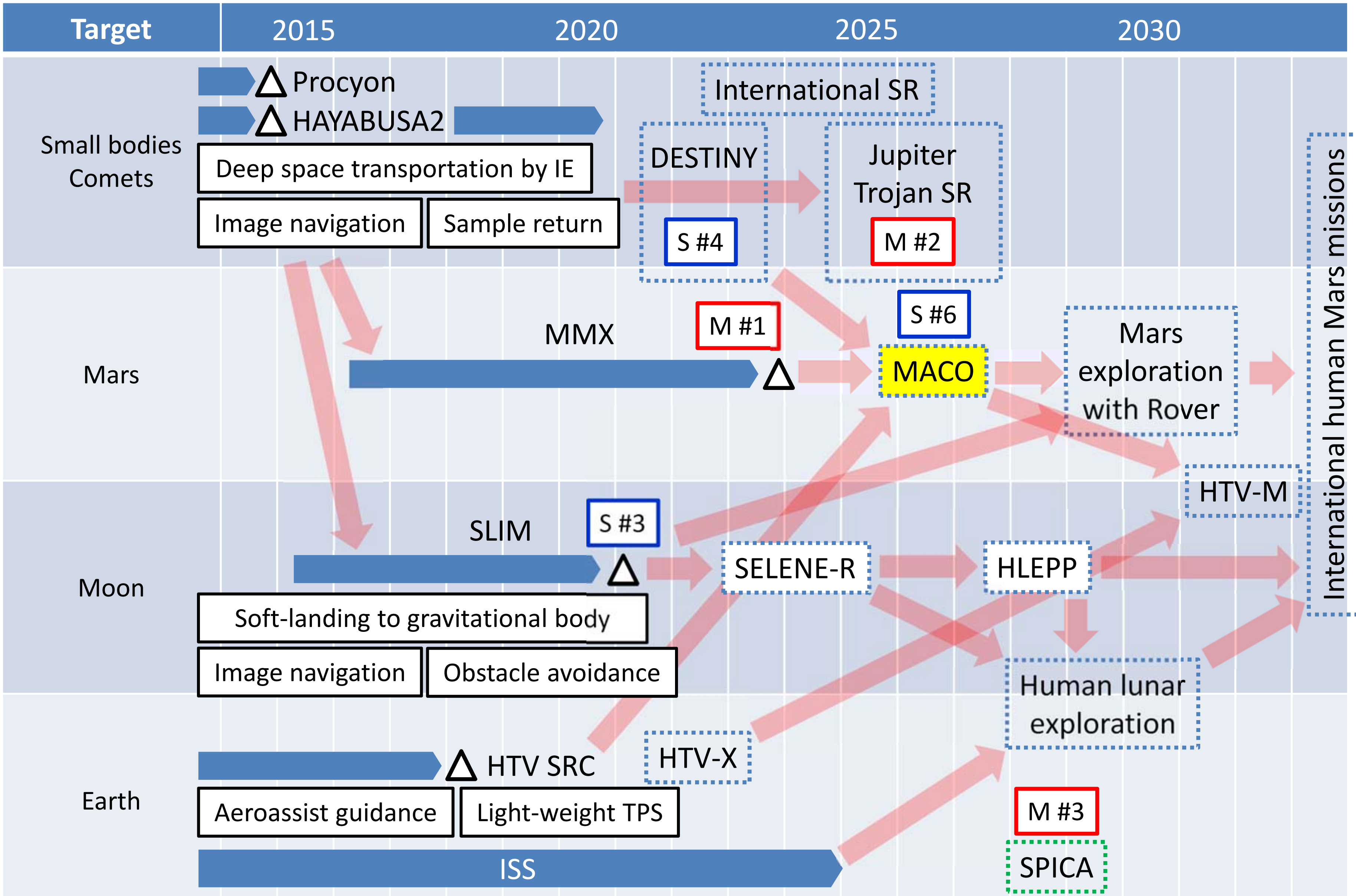
Strategy of Mars Exploration

- In the situation that not only NASA and ESA have performed but also Asian countries are planning Mars exploration in 2020s, if Japan launches a Mars exploration, its significance, purpose, and outcome will be strongly questioned. The key word may be novelty and originality, and bold challenges with high creativity will be needed for exploration engineering.
- Meanwhile, to realize Mars surface mission that the JSPS supports, secure and step-by-step acquisition of EDL technology is needed (security & reliability > novelty & originality).
- Mars Aerocapture Obiter as a small-class mission must be a best solution for this question, following MMX, leading to Mars surface missions, and performing high cost effectiveness.

Mission Objectives and Expected Results

Mission Objectives	Expected Results
To insert a Mars orbiter by aerocapture	Partial demonstration of EDL technologies required for future surface missions (technical continuity), and the world's first acquisition of AC technology.
To provide platform functions for surface missions (data relay, EDL support etc.)	International cooperation for existing platforms / provision for future Japan's surface missions.
To provide platform functions for long-term scientific observation of Martian environments	Realization of remote-sensing, Martian space weather & climate exploration observation, etc.
	Acquisition of information required for landing point selection in future surface missions.

Casting in Exploration Roadmap (Proposed)



Orbit Planning (1/2)

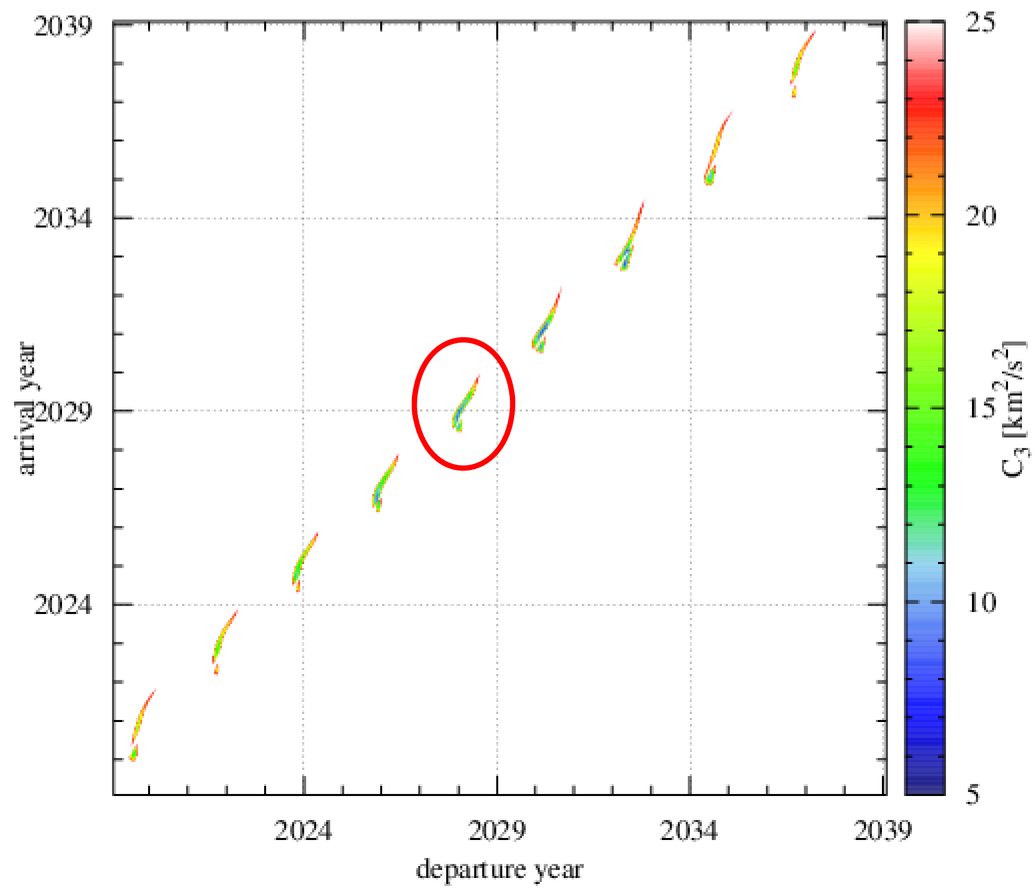
Mars Transfer Orbit

- Launch @ 2026/10/31, Arrival at Mars on 2027/08/20 (0 rev. about sun)
- Arrival C_3 = 7.36 km^2/s^2 (V_∞ = 2.713 km/s)

Launch Capability of Epsilon

- Similar to SLIM (using KM)
- Assessed as TMI from SLIM IF orbit (250 x 19,000 km)

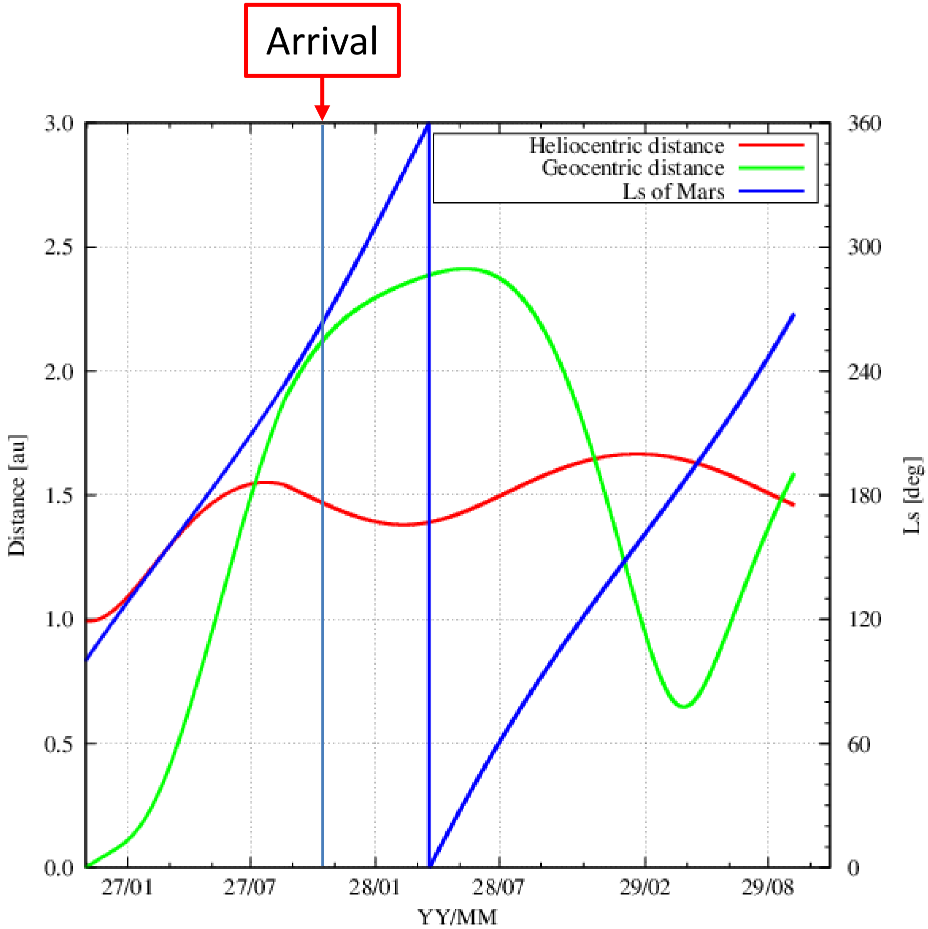
Launch epoch	2026 window
Departure C_3	9.18 km^2/s^2
TMI ΔV	1.61 km/s
TMI WET Mass (Isp =310 s)	323 kg
Arrival C_3	7.36 km^2/s^2
Arrival V_∞	2.713 km/s
Flight time	293 days

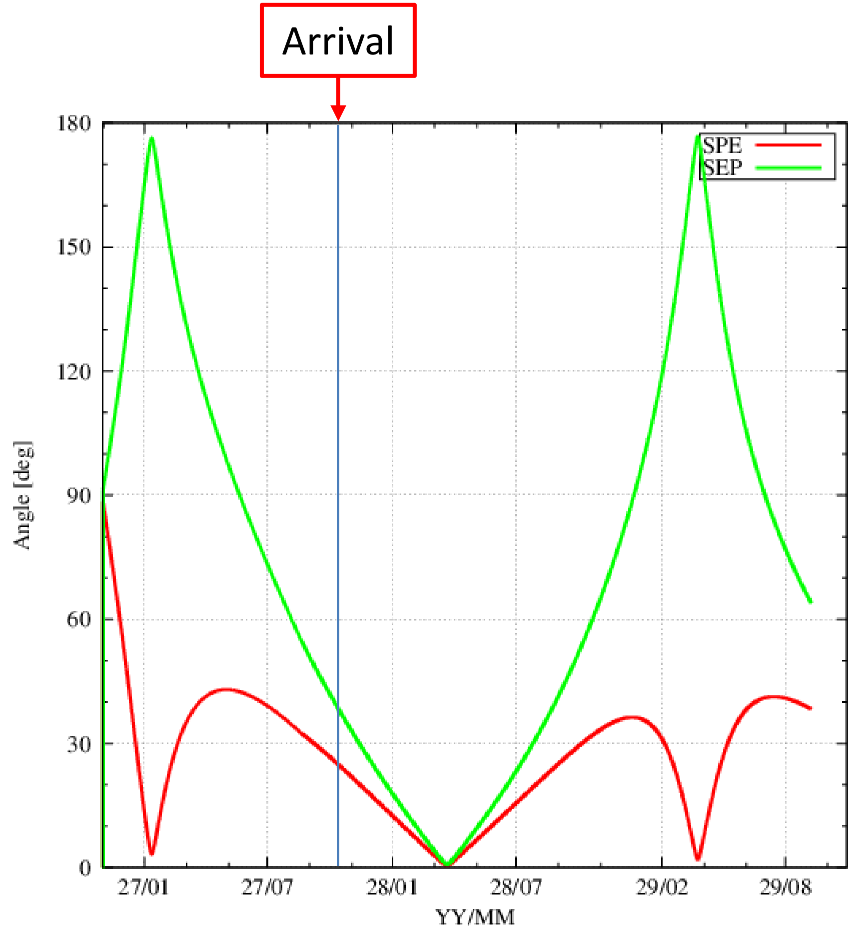


Orbit Planning (2/2)

Visibility & Communicability on Arrival

- Distance from Earth is 2.2 AU (relatively long but communicable)
- SEP = 38° (not bad). Conjunction occurs 2.5 month after MOI (late enough for initial operation).





Aerocapture Corridor Assessment (1/2)

Trans-Mars Orbit

- Launch on 2026/10/31, Mars arrival on 2027/8/20 (L_s = 148.5) as previously defined (0 rev.)
- Arrival V_∞= 2.713 km/s,

Mars Atmosphere Model

- Nominal, High-density, Low-density models are developed for arrival epoch by using Mars-GRAM 2005 v13.
- Nominal model is defined as a daily and global average, while high-density and low-density models are defined as upper and lower limits with +5σ and –5σ dissipations, respectively.

Mars Gravity Model

- Martian surface is assumed as a spheroid.
- Mars gravity is assumed as a mass point located at the spheroid center.

Aerocapture Procedure & Target Orbit

- Based on mission requirement from Martian Space Weather & Climate Exploration Mission, a 300×5,000 km polar orbit synchronized with Mars rotation is selected as the target orbit.
- After deceleration by atmosphere, periapsis raise maneuver is conducted to raise the periapsis altitude to 300 km at the first apoapsis, then apoapsis altitude is adjusted to 5,000 km by apoapsis adjust maneuver at the second periapsis.

Assessment of Aerocapture Corridor (2/2)

Constraint Conditions on Post-Aerocapture Maneuver

1. The total post-aerocapture ΔV (the sum of periapsis raise and apoapsis adjust maneuver ΔV) should be less than 100 m/s. This constraint is required for aerocapture to be superior to propulsive orbit insertion with respect to mass budget.
2. The first apoapsis after atmospheric exit should be less than 30 Rm (the orbiter should be safely captured by Martian gravity). This is automatically satisfied when 1 is fulfilled.
3. Flight time from atmospheric exit to the first apoapsis should be greater than 30 minutes. This period is required for attitude determination and attitude control prior to periapsis raise maneuver.
4. Corridor width should be wider than 3°. According to past studies, orbit determination by using DSN realizes flight path angle accuracy within 0.1°.

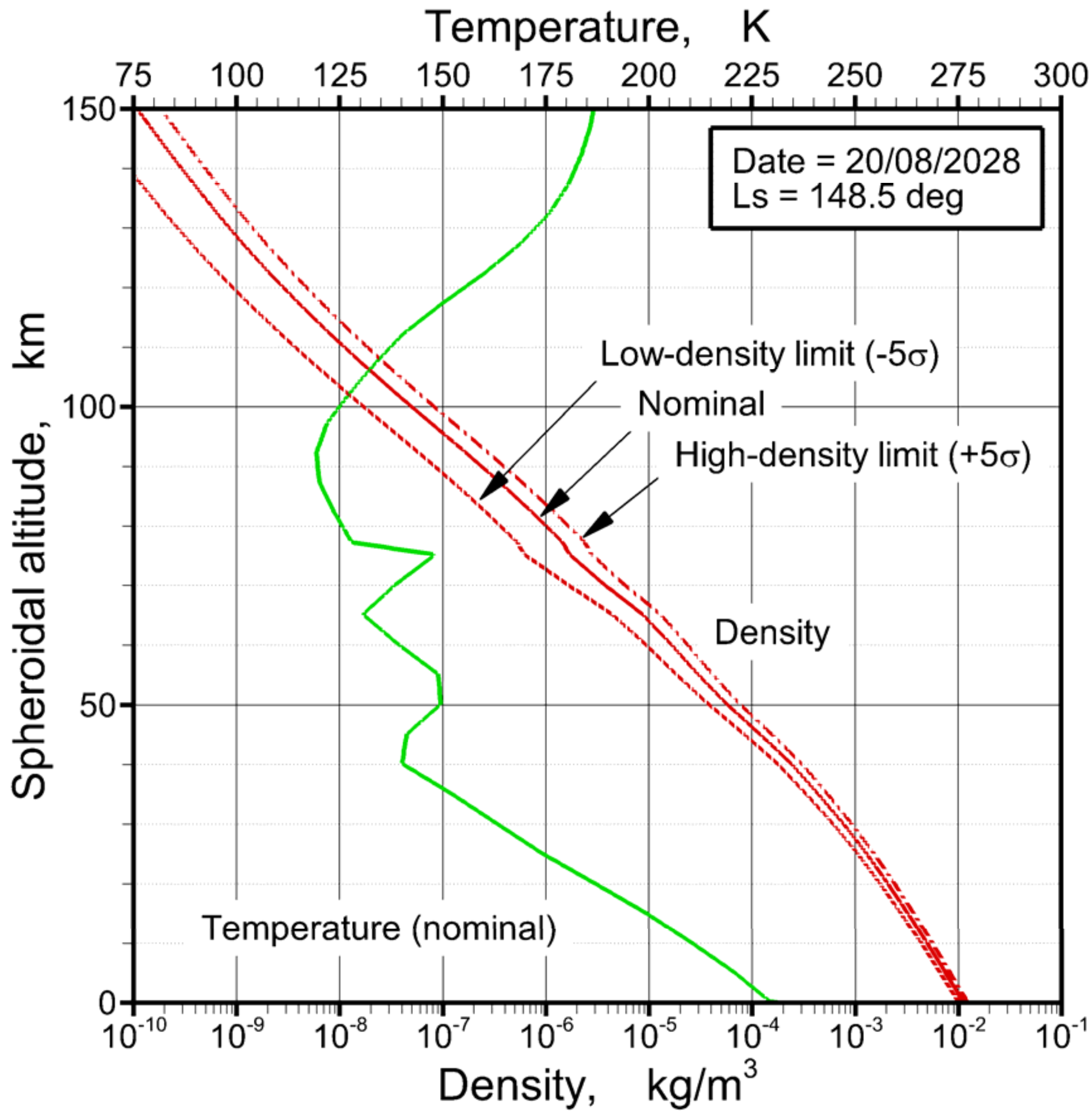
Parameters	Unit	Errors (±3σ)
Position error (X)	m	12459.5
Position error (Y)	m	3058.6
Position error (Z)	m	5482.5
Velocity error (magnitude)	m/sec	8.356
Velocity error (flight path)	deg	0.06
Velocity error (flight azimuth)	deg	0.04

Numerical Method

- Flight dynamics code *SDF28-012* is used in the mass-point mode (3-degrees-of-freedom).
- Range of flight path angle acceptable for aerocapture is determined by changing the ballistic coefficient from 10 to 1,000, and the lift-to-drag ratio (L/D) from –0.4 to +0.4.

Mars Atmosphere Model

- MarsAtmosphere-20270820



Aerocapture Corridor & Design Point

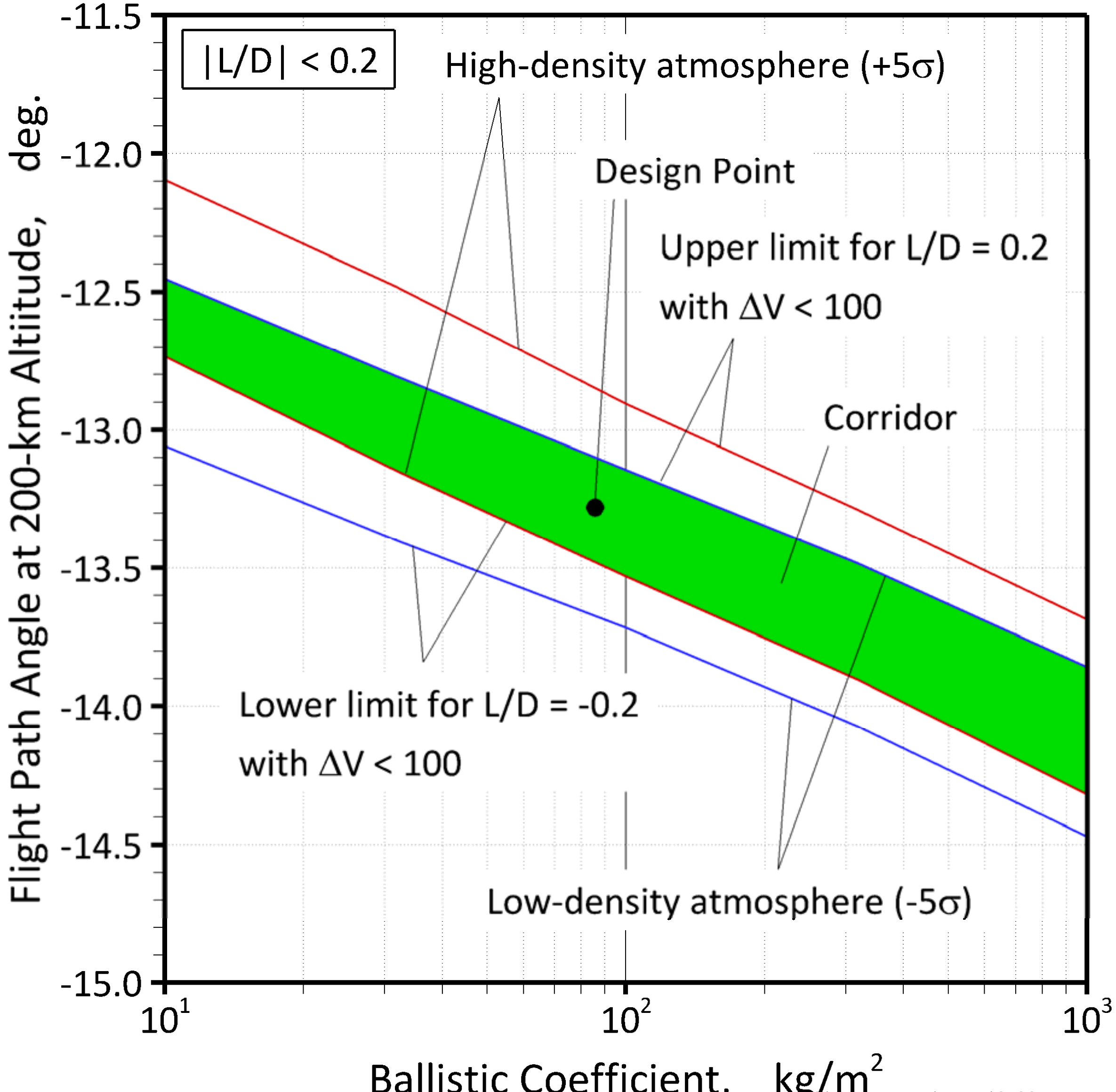
Design Point

- β = 85.7 kg/m^2
- |L/D| = 0.2
- γ = – 13.28°

Corridor Characteristics

- $\Delta\gamma$ = 3.2° (> 3.0°)
- Post aerocapture ΔV < 100.0 m/s

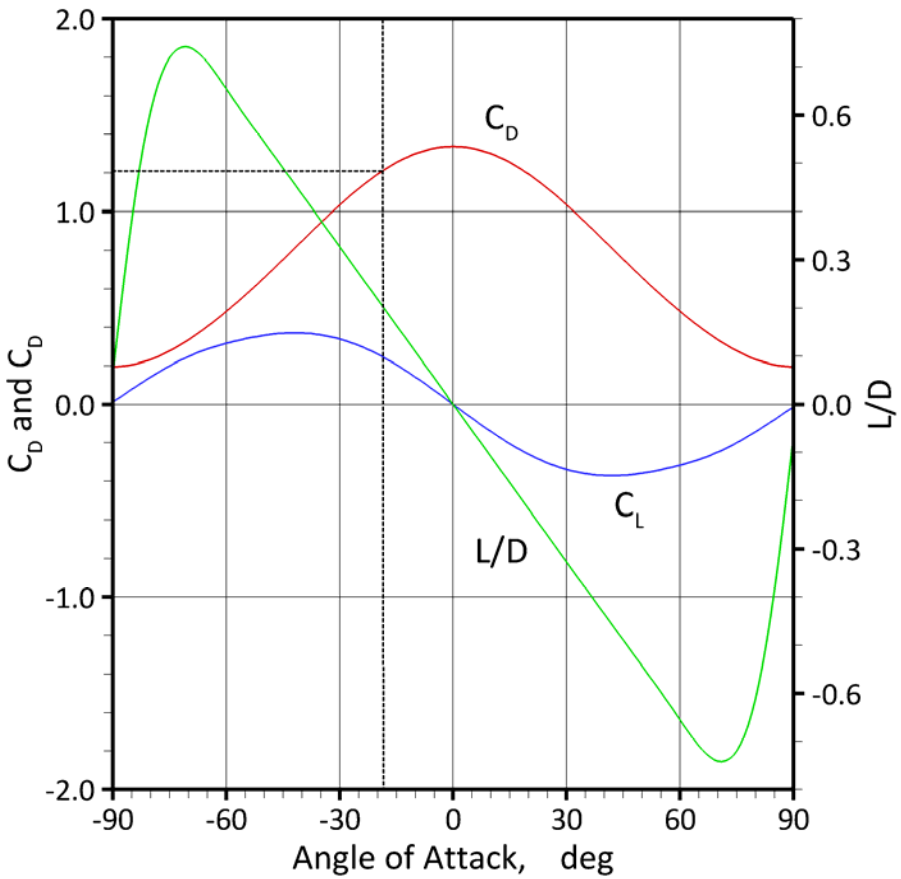
  (minimum = 46.3 m/s)

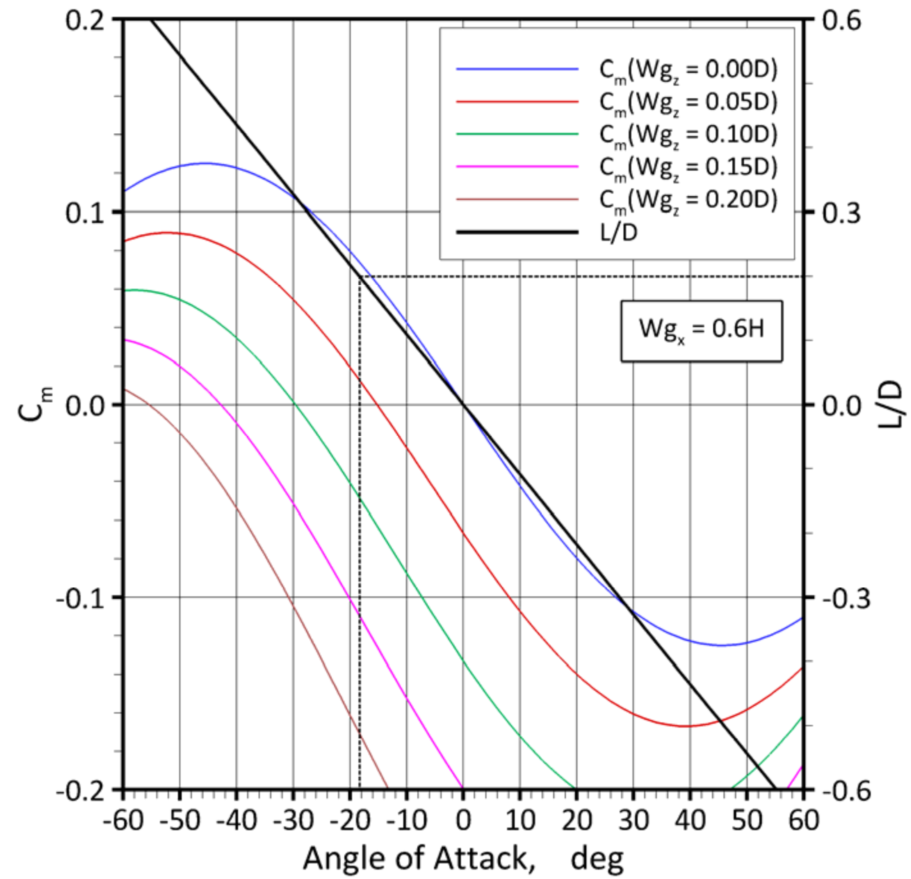


Aerodynamic Shape Definition (1/2)

Influential Parameters for Aerodynamic Shape

- Dependence of L/D on angle of attack (linear)
- Sensitivity to center of gravity (small)
- Aerodynamic heat transfer rate (small)
- Stability around trim angle (high)
- Accommodatability (high)
- Surface to volume ratio (low)

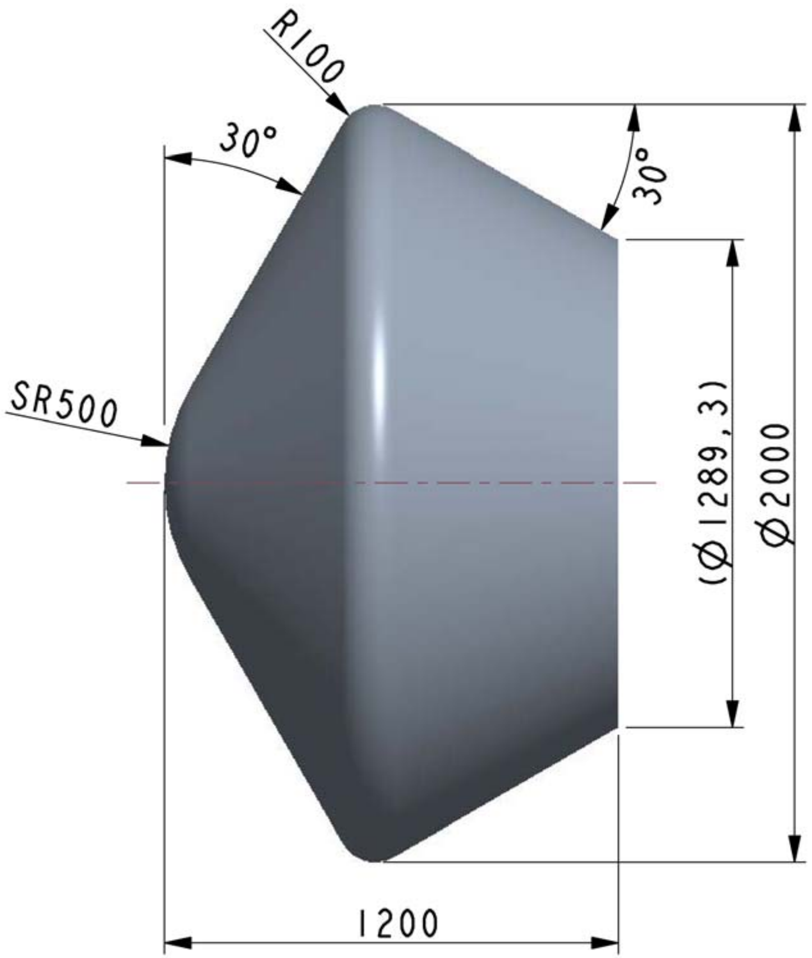


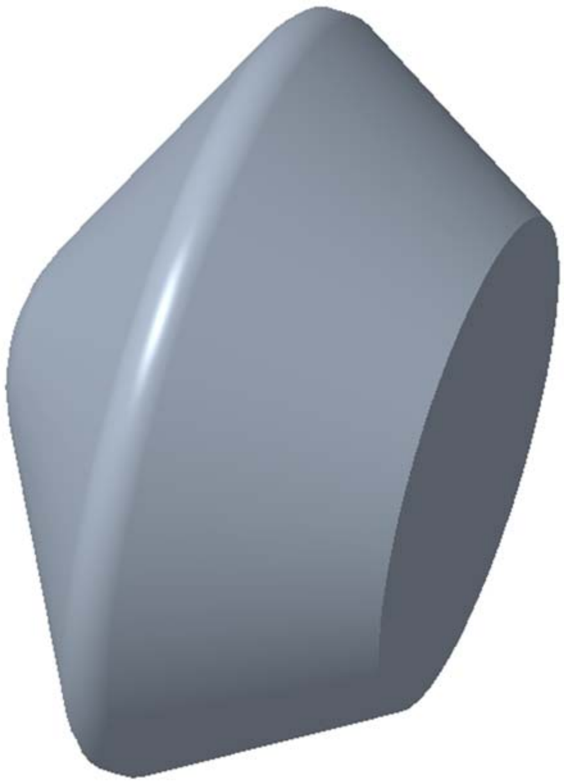


Aerodynamic Shape Definition (2/2)

Aerodynamic Shape Optimized for Aerocapture

- Half cone angle of 60° is favorable rather than 70° (Viking-type aeroshell).

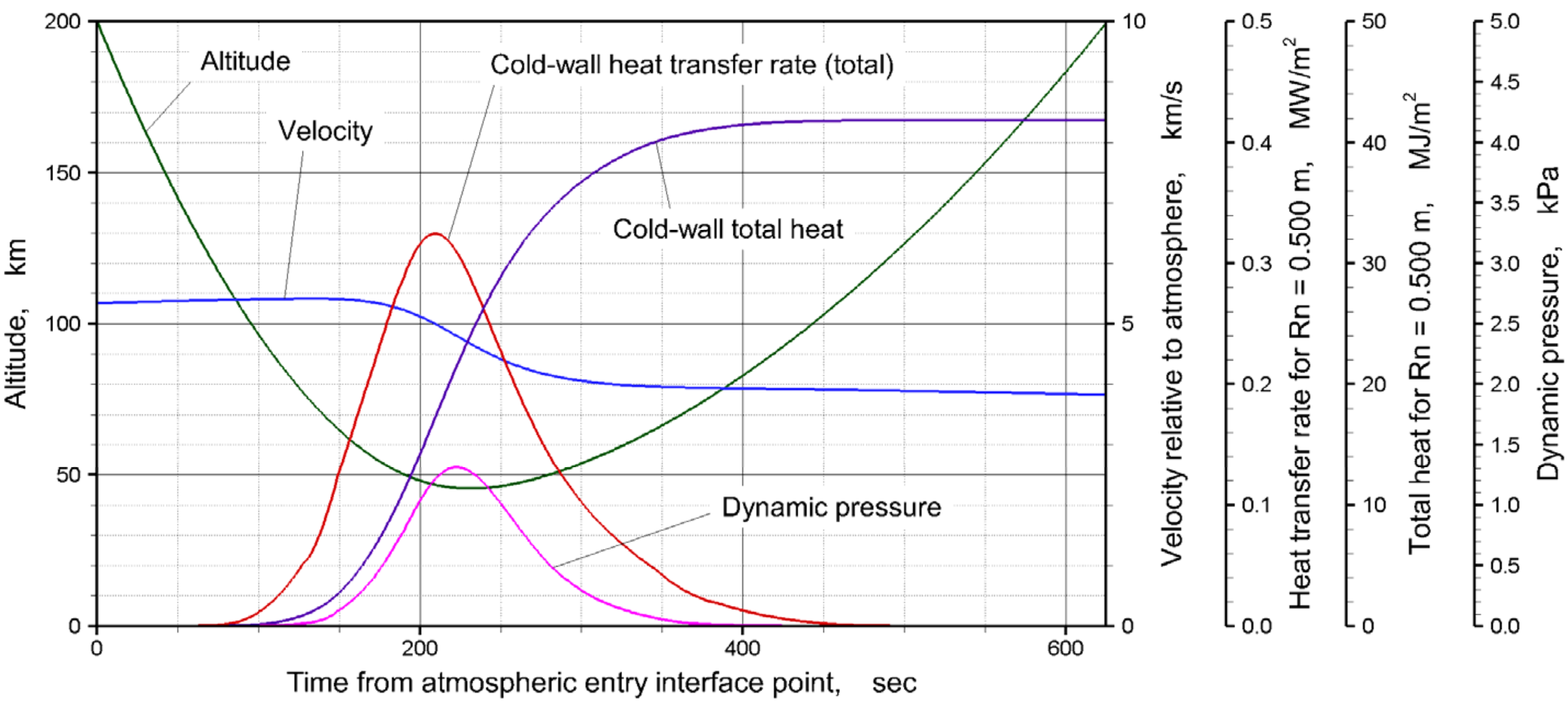




Aerocapture Orbit Baseline

TRJ-20270820-180110

- Peak heating is about 0.32 MW/m^2 at stagnation point. Total heat is 42 MJ/m^2.
- Peak dynamic pressure is approximately 1.3 kPa.
- Baseline orbit data are given as *TRJ-20270820-180110.dat*



Summary of Design Parameters

Parameters	Specification	Remarks
V_∞, km/s	2.713	
Total mass (WET), kg Aeroshell mass, kg Others, kg	323 45+24 254	Forebody + Aftbody
Aeroshell diameter, mm	2,000	Storable in Epsilon fairing
Aeroshell height, mm	1,200	Storable in Epsilon fairing
Atmospheric entry I/F altitude, km	125	
Ballistic coefficient (β), kg/m^2	85.7	C_DS = 3.77 m^2
C_D	1.20	
L/D	0.2	Trim angle of attack = −18°
Flight path angle, deg	−13.28°	
Corridor width (Δγ), deg	0.32	> 0.3° (requirement)
Periapsis altitude (target), km	300	
Apoapsis altitude (target), km	5,000	
Apoapsis altitude range (3σ), km	4,870 to 5,050	Adjusted after MOI

Communication Subsystem Design

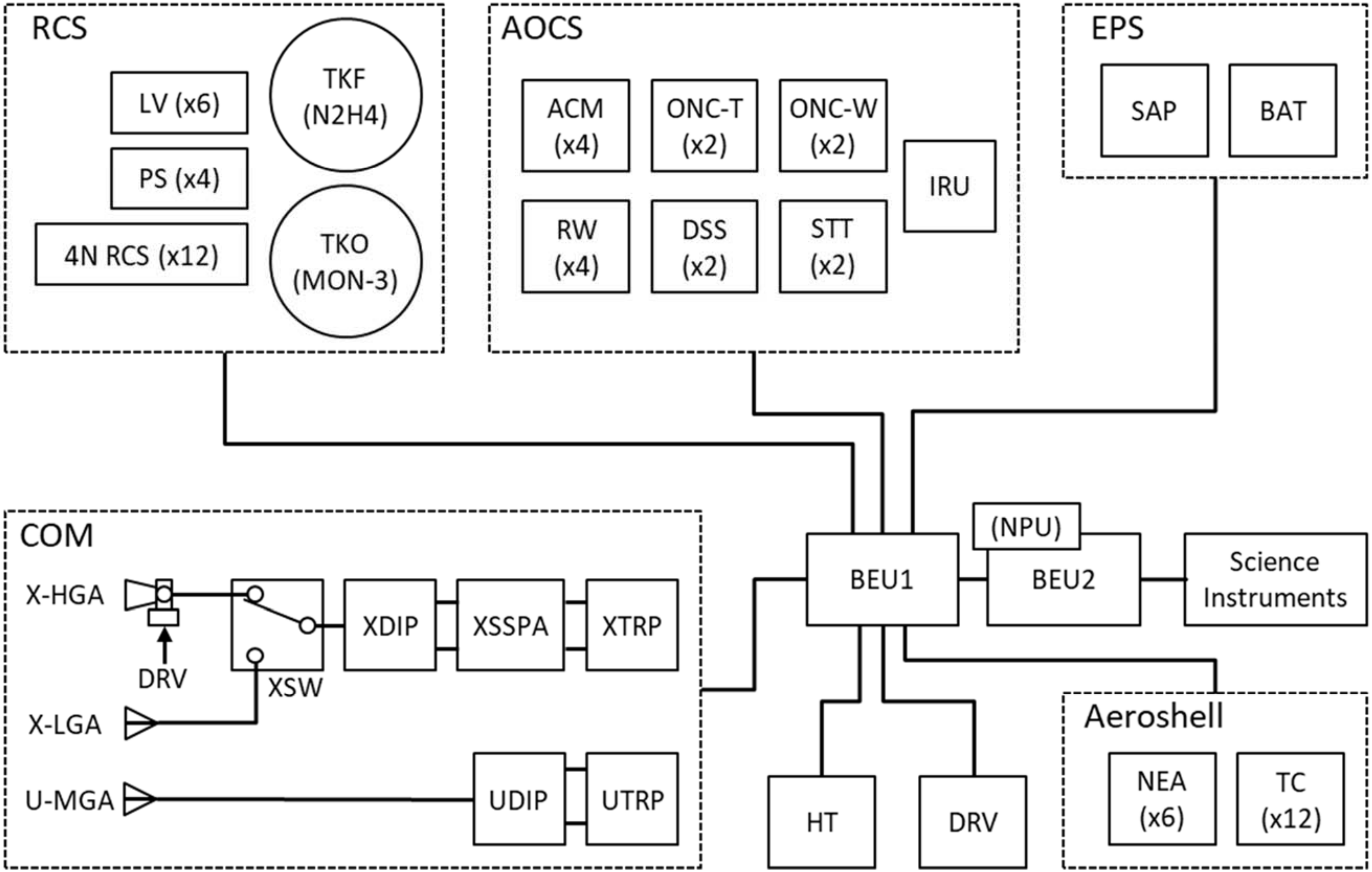
Orbiter-Ground

AU			XHGA		XMGA		XLGA (beacon)	
			ϕ0.3m	ϕ0.4m	(Boresight)	(±12.5deg)	(Boresight)	(±60deg)
1.2	TLM	bit rate (bps)	1024	2048	256	128	N/A	
		margin (dB)	2.3	1.8	3.1	2.4		
		status	OK	OK	OK	OK		
	carrier	margin (dB)	4.3	6.8	3.9	4.2	6.2	0.2
		status	OK	OK	OK	OK	OK	NG
1.54	TLM	bit rate (bps)	512	1024	128	64	N/A	
		margin (dB)	3.1	2.6	3.8	2.9		
		status	OK	OK	OK	OK		
	carrier	margin (dB)	6.9	4.6	5.7	4.7	4	-2
		status	OK	OK	OK	OK	OK	NG
2.25	TLM	bit rate (bps)	256	512	64	16	N/A	
		margin (dB)	2.3	2.1	3.2	4.1		
		status	OK	OK	OK	OK		
	carrier	margin (dB)	10.2	10	5	6.1	0.7	-5.3
		status	OK	OK	OK	OK	NG	NG

Mars Surface – Orbiter

- UHF Channel based on Martian data-relay standard
- By using Electra-Lite manufactured by L3 CCE, which is a standard compliant product, a bit rate higher than 64 kbps is possible.

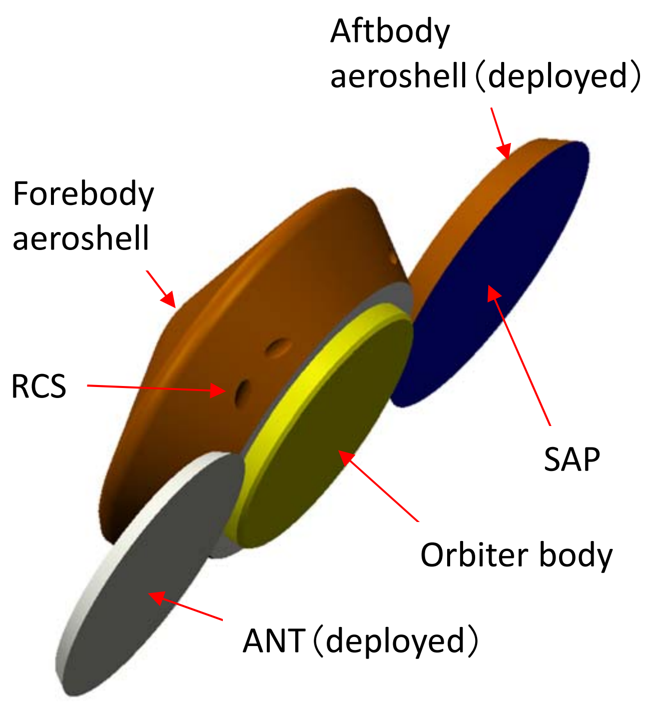
Block Diagram



System Configuration

Subsystem	Mass, kg	Remarks
Aeroshell Forebody Aftbody	69 45 24	Advanced NALT aeroshell is assumed.
COM X-band (LG, to Earth) X-band (HG, to Earth) U-band (to Mars)	40 0.4 22.6 17	Redundant 2 system
AOCS	14.4	
DHS	10.6	
RCS Propellant HW (4N RCS ×12) Tank & tubing	59 32 5 22	Combined system, 2-liquid
TCS	5	
EPS	23	SAP = 1.5 m^2, 1.2kWh/sol 300 Wh Li-ion battery
STR	38	Combined with aeroshell
INT	14	
Scientific Instruments	30	Mars Space Weather & Climate Instruments etc.
Margin	20	
Total	323	

Conceptual View of MACO



Comparison to Propulsive Orbit Insertion

Direct MOI by Chemical Propulsion

- ΔV required for direct MOI into a 300×5,000 km orbit with V_∞= 2.713 km/s is 1.514 km/s.
- Propellant mass ratio for propulsion system with Isp = 315 sec is **38.8 %**. Assuming structural coefficient of 0.25 for the propulsion system, mass ratio of the propulsion system is **48.5 %**.

- Mass ratio of the aerocapture subsystem is estimated to be **42.4%** in a conservative analysis, even considering all the propulsion subsystem HW, which is expected to be more advantageous than MOI by the propulsion system.

  Note: this advantage is degraded when propulsive MOI is combined with aerobraking after MOI, since aerocapture MOI cannot enjoy mass reduction by aerobraking.

Technical Problems

Deployment Technology

- For thermal control and power generation, the aftbody aeroshell has to be deployed during interplanetary flight, closed before atmospheric entry, and redeployed after atmospheric exit. Genesis is a good reference.

Communication Subsystem

- A small-sized X-band communication system with high-gain antenna is needed.
- A U-band communication system compliant with Mars communication standard is needed. Currently, the conceptual study result by MEISEI ELECTRIC CO., LTD. is used.
- A gimbal mechanism to control the direction of antenna may be needed.

Attitude Orbit Control Subsystem

- A small-sized AOCS with RWs is needed, since three axis attitude control is preferred for data-relay and science missions.

Aeroshell Subsystem

- Further lightweight aeroshell than current BBM is desirable.

Propulsion Subsystem

- Current RCS is applicable, but embedment of RCS in deployable aeroshell is difficult problem.

Redundancy

- HW redundancy is applied only to COM and DHS because of limited mass budget. Other type of small-sized bus system with sufficient redundancy will be entertained in the future.

Summary

- Conceptual Study of Mars Aerocapture Orbiter (MACO) has been conducted.
- Based on an Epsilon-Enhanced Launcher Equivalent to SLIM (combined with a KM), MTI Mass as Large as 323 kg is Expected for 2026 Launch Window.
- Within a Mass Budget of 323 kg, an Aerocapture Orbiter Including 30 kg of Scientific Instruments (Mars Space Weather and Climate Mission) is Considered to be Possible.
- Major Key Technical Issues to be Solved Have Been Extracted.

- From Here on, in Cooperation with Mars Remote Sensing Mission, Mars Space Weather and Space Climate Exploration Mission, and Mars Atmosphere Exploration Mission etc., More Detailed System Study will be Conducted to Create a Small Science Mission Proposal to be submitted to AO in 2018 or later.