[32th Workshop on JAXA Astrodynamics Symposium and Flight Mechanics C003]

Impact Probability Analysis for Planetary Protection of Martian Moons eXploration

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Agenda

- Martian Moons eXploration
- Planetary Protection
- Impact Probability on Mars
- Impact Probability on Europa and Enceladus
- Summary

Martian Moons eXploration

Martian Moons eXploration

○ MMX (Martian Moons eXploration)

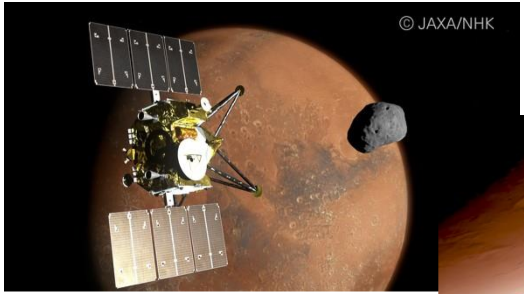
- ○ **World's first mission** to land on a Mars satellite Phobos, collect samples, and return to Earth

○ Purpose

- ○ Improved technology for going to and from the Martian atmosphere and advanced sampling techniques on the surface of celestial bodies
- ○ Clarify the origin of the Martian satellites and the evolutionary process of the Martian atmosphere

○ Main Mission

- ○ Operation on quasi satellite orbit (QSO)
- ○ Descent, landing and ascent to Phobos
- ○ Deimos flyby



◀ Earth to Mars

Landing on Phobos ▶

Trajectory Planning for MMX

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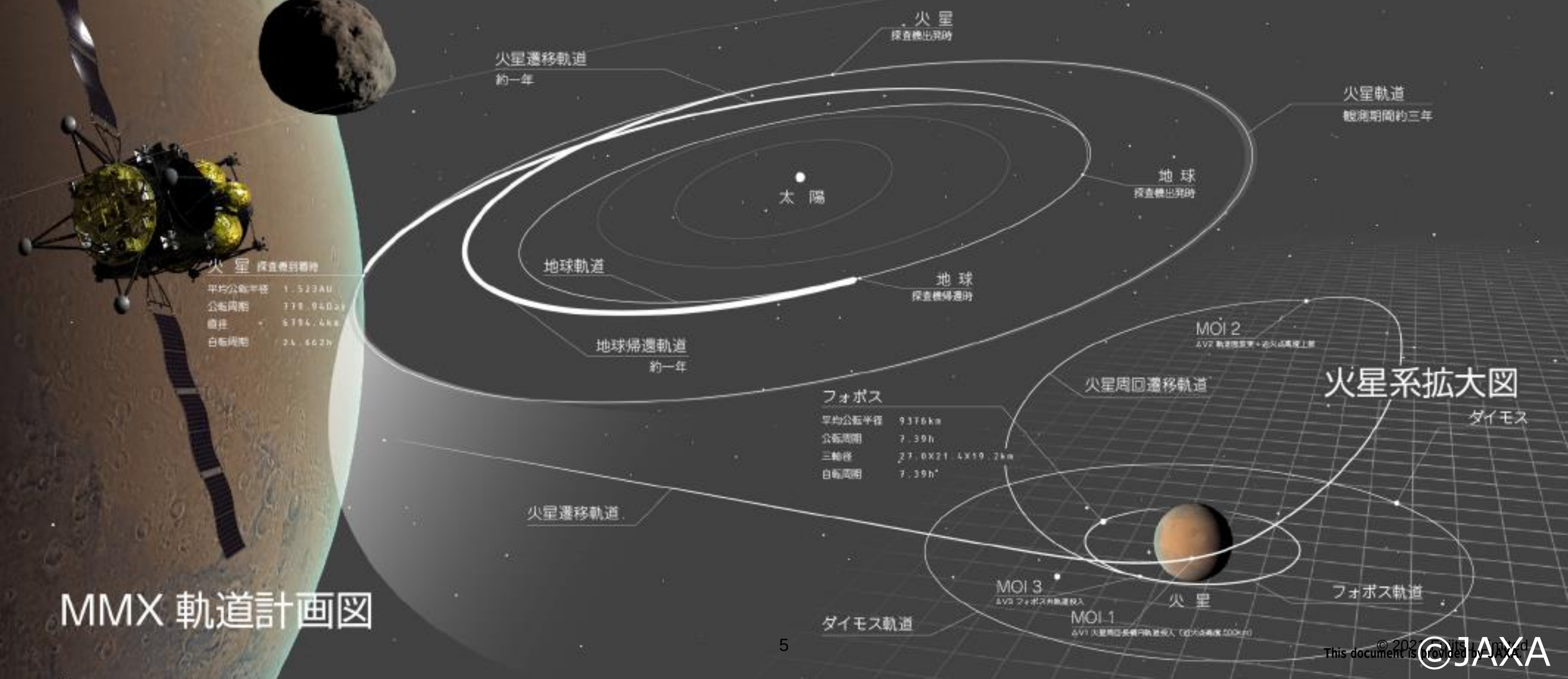
- Trajectory Planning = creating a path for the spacecraft to follow



Trajectory Planning for MMX

○ Trajectory Planning in Each Phase

No	Phase	Main Control Plan
1	Outbound	Separation, BCM1/2/3/4
2	Mars Orbit Insertion (MOI)	MOI1/2/3
3	Mars Neighborhood	Phasing and Insertion into QCO, Landing
4	Mars Orbit Escape (MOE)	Deimos flyby (MOE1.0/1.1/1.2/1.3/1.4/1.5), MOE2
5	Inbound	MOE3, TCM

Planetary Protection

Planetary Protection

○ Planetary Protection

- ○ Activities related to the development and operation of spacecraft in accordance with the Planetary Protection Policy (PPP) of the International Committee on Space Research (COSPAR)

1. **Protection of the environment in Earth-Moon system**
   Protect Earth from life forms on other celestial bodies

2. **Conservation of objects to be explored**
   Protect other celestial bodies from contamination by life on Earth
   → The impact probability with a target celestial body
   by a rocket, debris and spacecraft having the orbital energy
   to reach the target celestial body shall be less than the specified value

Perform impact probability analysis as a position in charge of trajectory planning

Collision probability for planetary protection

○ Assumptions (based on Planetary Protection Policy PPP)

- ○ Category V
  Objects to be protected: Mars, Europa, Enceladus

- ○ Impact probability = Σ(failure probability of spacecraft × impact probability after failure)
  * This analysis deals with the impact probability after failure

- ○ Impact probability must be less than 1×10-4 for 50 years after launch

Purpose :
calculate the impact probability based on PPP and confirm that the impact probability is less than the specified value
① Impact Probability on Mars
② Impact Probability on Europa and Enceladus

Impact Probability on Mars

Trajectory Planning for MMX

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○ Trajectory Planning in Each Phase

No	Phase	Main Control Plan
1	Outbound	Separation, BCM1/2/3/4
2	Mars Orbit Insertion (MOI)	MOI1/2/3
3	Mars Neighborhood	Phasing and Insertion into QCO, Landing
4	Mars Orbit Escape (MOE)	Deimos flyby (MOE1.0/1.1/1.2/1.3/1.4/1.5), MOE2
5	Inbound	MOE3, TCM

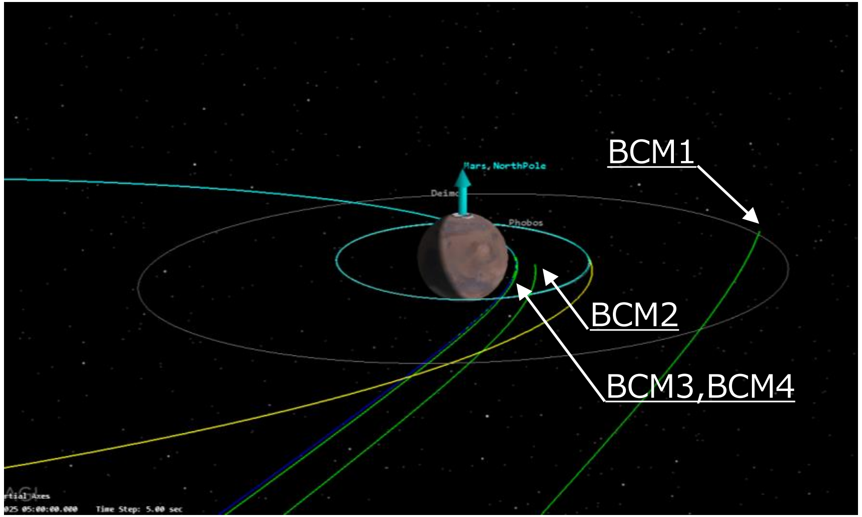
Step1: Overview of trajectory planning in each phase
Step2: Impact probability analysis for control plans in each trajectory plan

Outbound

○ Trajectory Plan

- ○ Trajectory Biasing: Target aim points offset from Mars
- ○ Plan TCM (BCM) to change aim points step by step and move closer to Mars
  *BCM (Bias Correction Maneuver)

○ Control Plan



Event	Epoch [UTC]	dV [m/s]
Separation	30 Sep 2024 02:17:48.484	-
BCM1	10 Feb 2025 04:24:24.366	6.42496
BCM2	20 Feb 2025 04:24:24.366	0.748598
BCM3	2 Mar 2025 04:24:24.366	0.11677
BCM4	14 Aug 2025 05:00:00.000	0.238031

◀Trajectory Biasing

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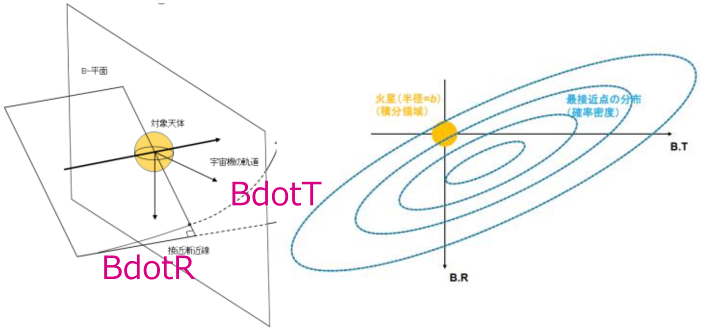
Outbound (Separation)

- Analysis Contents
  - Impact probability for cases in which the spacecraft malfunctions after rocket separation and subsequent maneuvers cannot be performed
  - Monte Carlo analysis of 50-year propagation given rocket separation error covariance
- Impact probability calculation
  - The two-dimensional distribution (BdotT, BdotR) on the B-plane at the closest approach to Mars is a two-dimensional normal distribution
  - Integrate the probability density function over the area of a circle of collision radius (=7480[km])

probability density function: $p_b = \frac{1}{2\pi\sqrt{\det C_b}} \exp\left[-\frac{1}{2}\Delta r_b^T C_b^{-1} \Delta r_b\right]$

C_b: error covariance matrix of BdotT, BdotR
Δr_b: relative position vector to the closest approach position on B-plane

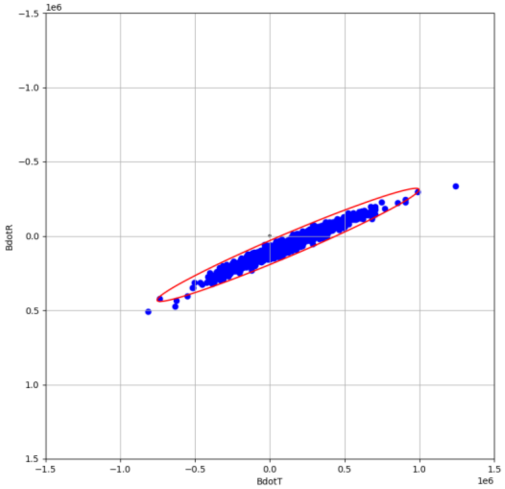
Impact Probability: $P_c = \frac{1}{2\pi\sqrt{\det C_b}} \int_{A_b} \exp\left[-\frac{1}{2}\Delta r_b^T C_b^{-1} \Delta r_b\right] dA_b$



Separation/2024

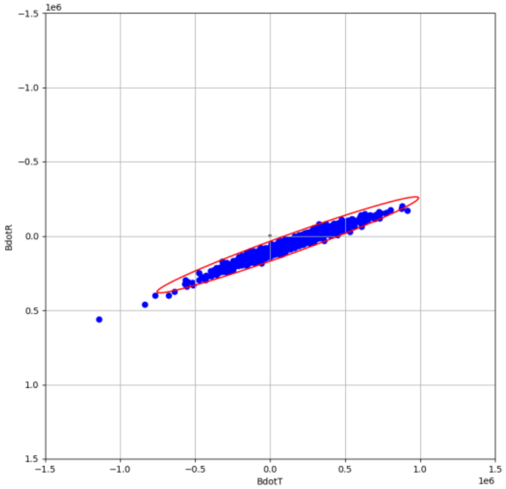
○ Distributions of BdotT and BdotR at the closest approach to Mars

open



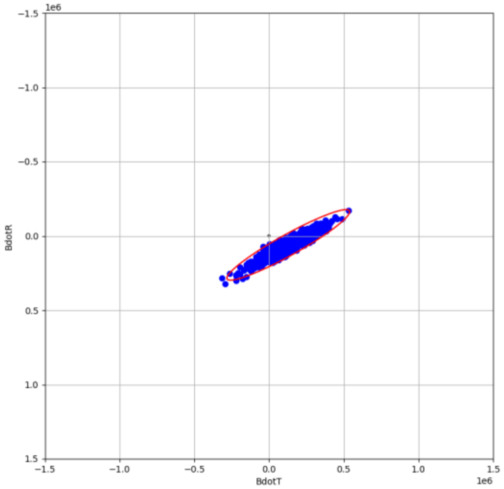
probability of impact: 7.2056e-08

nominal



probability of impact: 8.3006e-09

close



probability of impact: 1.3640e-09

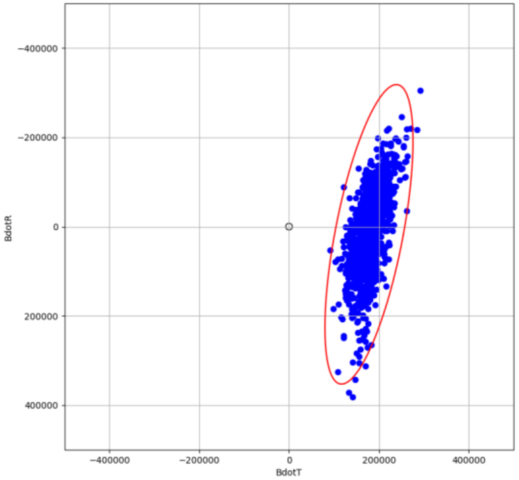
In all cases, the closest meeting is the first

*The red ellipse is the 3σ error ellipse

Separation/2026

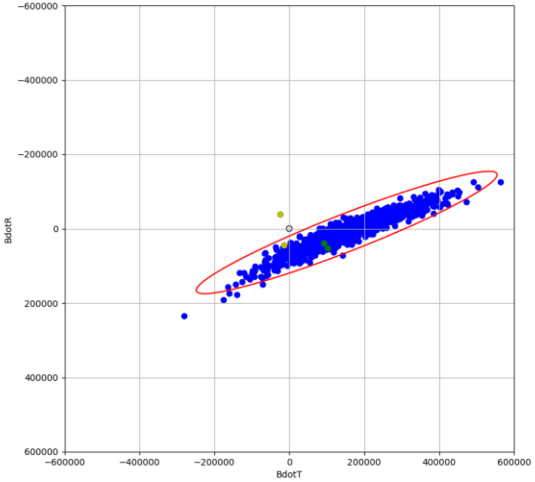
○ Distributions of BdotT and BdotR at the closest approach to Mars

open



probability of impact: 1.3236e-16

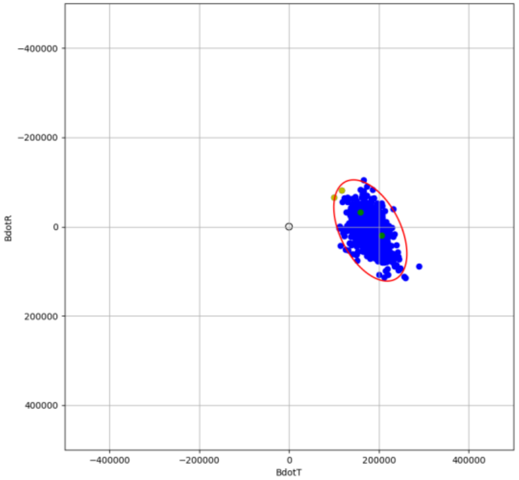
nominal



probability of impact: 5.7369e-07

cases where the closest is not the first: 2

close



probability of impact: 2.5666e-17

cases where the closest is not the first: 2

*The red ellipse is the 3σ error ellipse

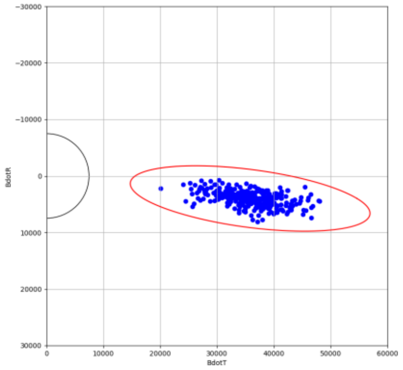
Outbound (BCM1/2/3/4)

- Analysis Contents
  - Impact probability for cases in which the spacecraft malfunctions after rocket separation and subsequent maneuvers cannot be performed
  - Monte Carlo analysis of 50-year propagation given dV error and orbit determination error
- Impact probability calculation
  - Same as rocket separation

BCM/2024/nominal

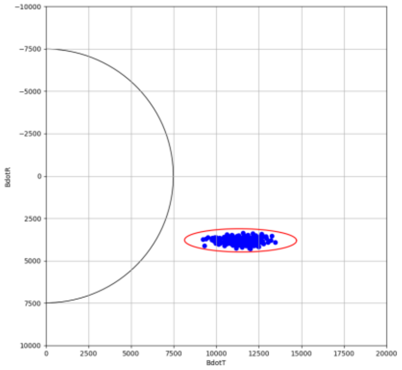
○ Distributions of BdotT and BdotR at the closest approach to Mars

BCM1



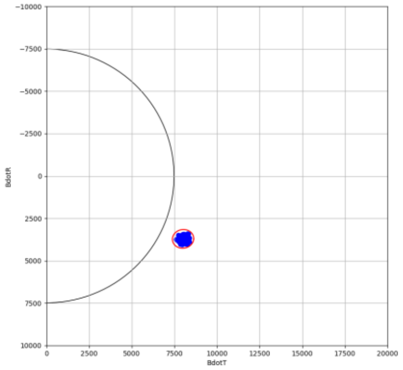
probability of impact: 3.7622e-09

BCM2



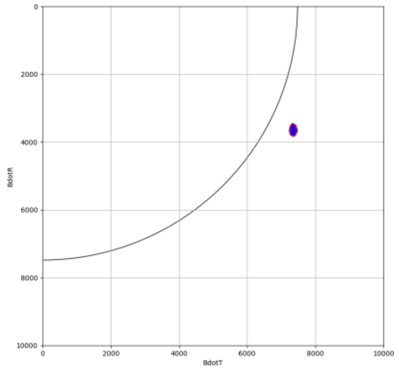
probability of impact: 7.8528e-11

BCM3



probability of impact: 7.7299e-22

BCM4



probability of impact: 2.0032e-201

impact probability of rocket separation + Σ impact probability of each BCM= 1.2141e-08

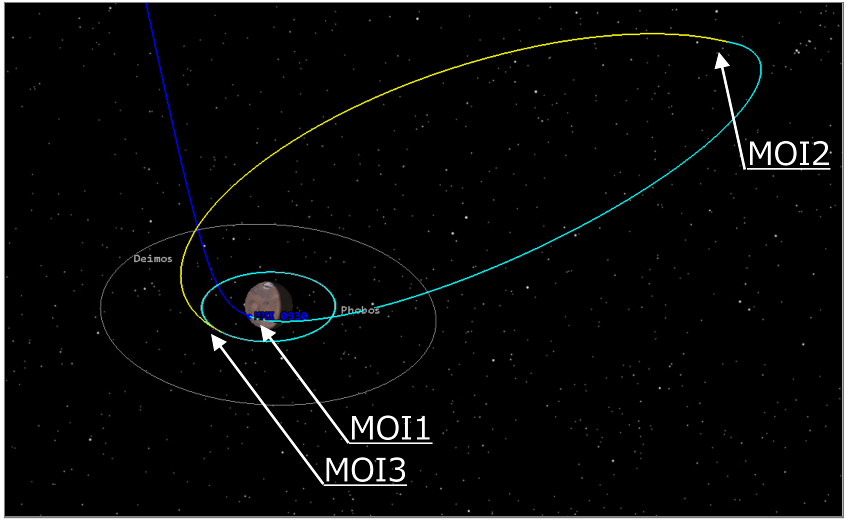
*The red ellipse is the 3σ error ellipse

MOI

○ Trajectory Plan

- ○ Insertion into Mars orbit by 3 divided MOI1 (peri), MOI2 (apo), and MOI3 (peri)
- ○ After MOI, separation of outbound module and insertion into the co-orbit with Phobos

○ Control Plan



Event	Epoch [UTC]	dV [m/s]
MOI1	14 Sep 2025 04:34:55.230	703.995
MOI2	17 Sep 2025 10:29:42.942	71.0647
MOI3	20 Sep 2025 21:02:43.144	785.976

MOI

○ Analysis Contents

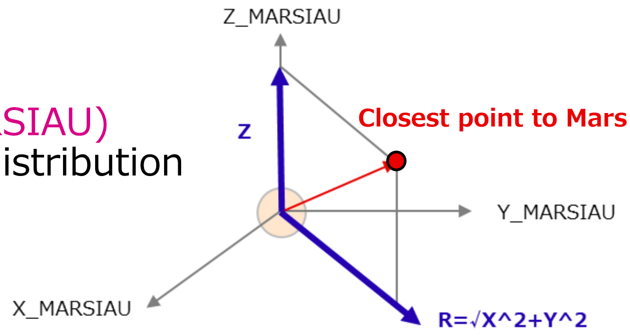
- ○ Impact probability for cases in which the spacecraft malfunctions after rocket separation and subsequent maneuvers cannot be performed
- ○ Monte Carlo analysis of 50-year propagation given dV error and orbit determination error

○ Impact probability calculation (MOI1)

- ○ Impact on Mars in most cases due to low periapsis altitude
- ○ Impact probability = impacts / trials (1000 cases) x failure rate of spacecraft

○ Impact probability calculation (MOI2/3)

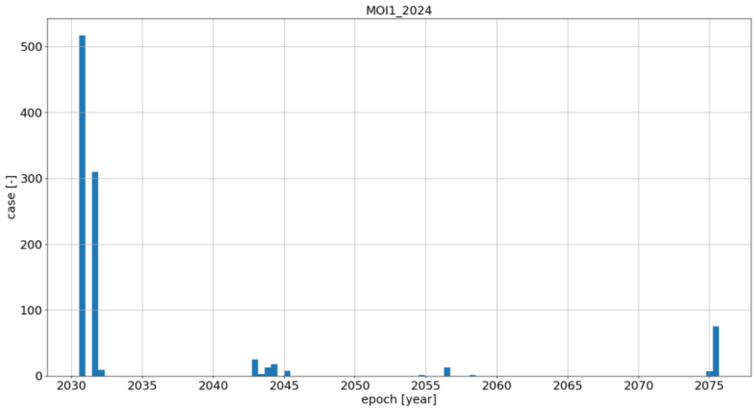
- ○ B-plane cannot be defined due to Mars orbit (elliptical orbit)
- ○ The two-dimensional distribution on the Rz-plane (SPICE/MARSIAU) at the closest approach to Mars is a two-dimensional normal distribution
- ○ Integrate the probability density function over the area of a circle of Mars radius

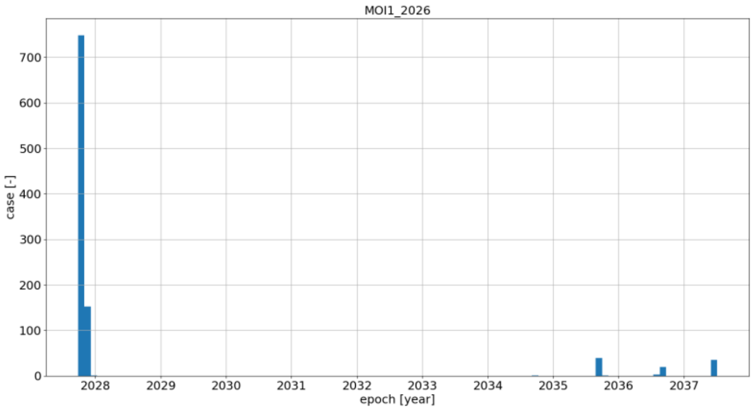


MOI1

○ 解析結果

- ○ **MOI1/2024** : 925/1000×(failure rate of spacecraft)
- ○ **MOI1/2026** : 1000/1000×(failure rate of spacecraft)

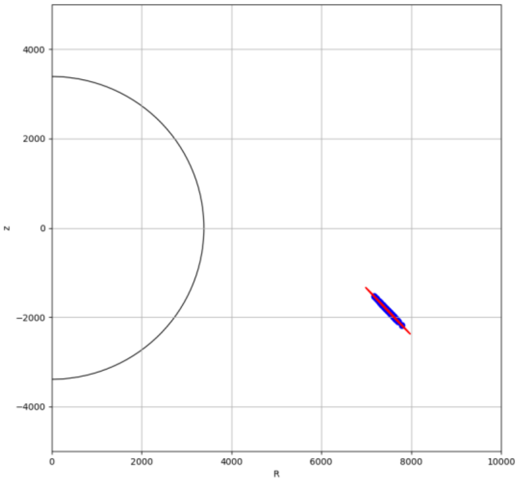




MOI2/3

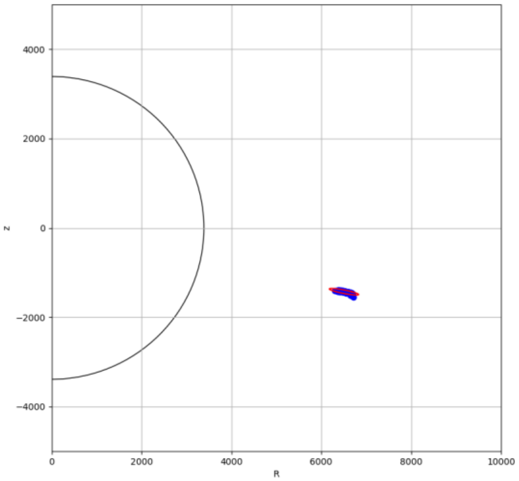
○ Distributions of Rz at the closest approach to Mars

MOI2/2024



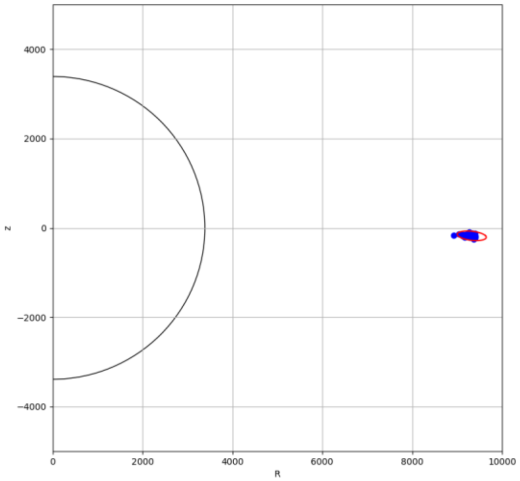
probability of impact: 0.0

MOI2/2026



probability of impact: 0.0

MOI3/2024



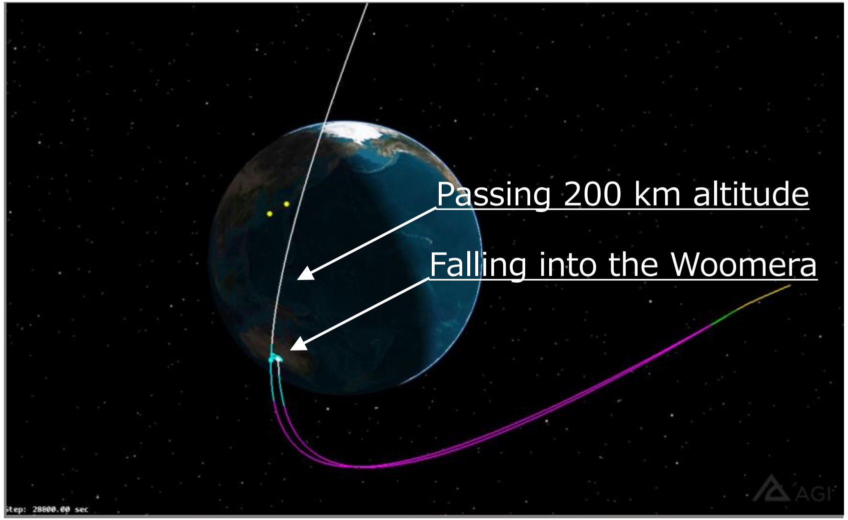
probability of impact: 0.0

Inbound

○ Trajectory Plan

- ○ Target a point biased 200 km above the earth's altitude by MOE3 → Earth swingby
- ○ Guide the spacecraft over the Woomera Desert by TCM (Trajectory Correction Maneuver)

○ Control Plan



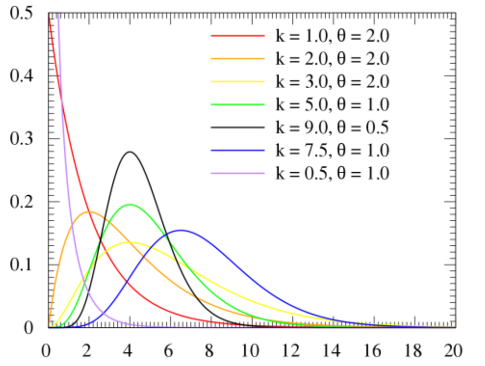
Event	Epoch [UTC]	dV [m/s]
MOE3	4 Sep 2028 23:30:00.000	657.116
TCM	27 Jul 2029 17:00:00.000	1.21428
Landing	5 Aug 2029 17:12:31.995	-

Inbound (MOE3)

- Analysis Contents
  - Impact probability for cases in which the spacecraft malfunctions after rocket separation and subsequent maneuvers cannot be performed
  - Monte Carlo analysis of 50-year propagation given dV error and orbit determination error
- Impact probability calculation
  - Not 2D normal distribution due to the scattered of Mars closest approach points
  - Fitting 1D distribution of Mars distance at the closest approach by gamma distribution
  - Integrate the probability density function of gamma over the area of a circle of Mars radius

Impact Probability: $p_r = \frac{1}{\Gamma(k)\theta^k}(x - loc)^{k-1}e^{-\frac{x-loc}{\theta}}$

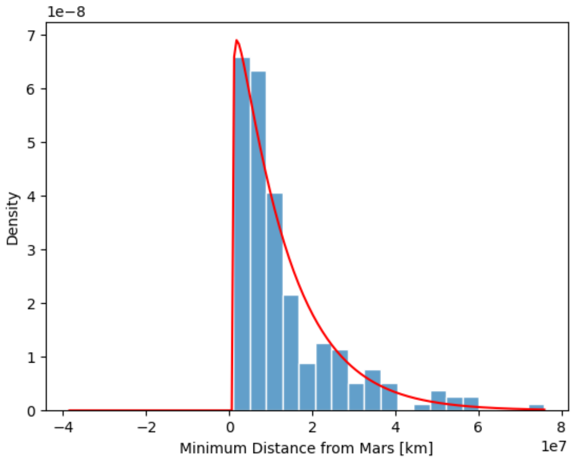
$\Gamma(k)$: gamma function
loc: offset value



MOE3

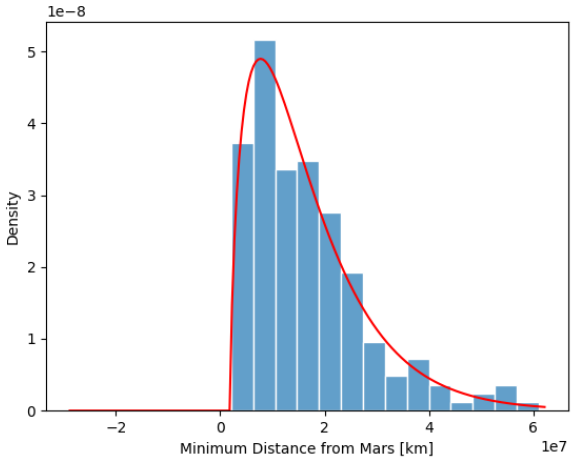
○ Distributions of Mars distance at the closest approach to Mars

MOE3/2024



k	1.069383705510063
θ	11639702.004048625
loc [km]	999601.0453087173
probability of impact	0.0

MOE3/2026



k	1.652093171955857
θ	8937644.858049646
loc [km]	1890426.6853572074
probability of impact	0.0

Impact Probability on Europa and Enceladus

Impact Probability on Europa and Enceladus

○ Energy Analysis

- ○ Analyze if there is an energy potential that could reach Europa or Enceladus

○ Analysis Method

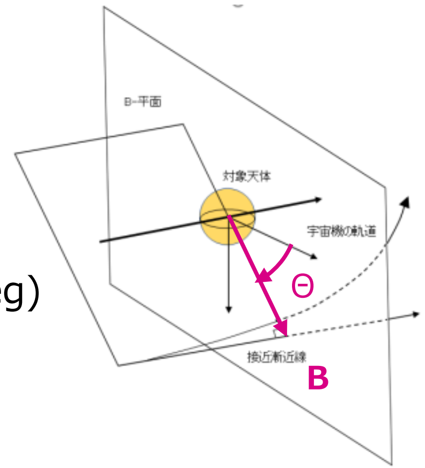
- ○ $\boldsymbol{V}_{\infty I}$: Incoming asymptote velocity
- ○ $\boldsymbol{V}_{\infty O}$: Outgoing asymptote velocity

$$\boldsymbol{V}_{\infty O} = |\boldsymbol{V}_{\infty I}| \left(\cos\phi_B \hat{\boldsymbol{S}}_I - \sin\phi_B \frac{\boldsymbol{B}}{b} \right)$$

$$\sin\frac{\phi_B}{2} = 1 \Big/ \left(1 + \frac{r_\pi |\boldsymbol{V}_{\infty I}|^2}{\mu} \right)$$

$$\boldsymbol{B} \cdot \hat{\boldsymbol{S}}_I = 0,\ \ \boldsymbol{B} \cdot \hat{\boldsymbol{T}} = b\cos\theta\,,\ \ \boldsymbol{B} \cdot \hat{\boldsymbol{R}} = b\sin\theta$$

r_π : closest distance
b: collision radius
θ: entry angle to B-plane (0-360eg)

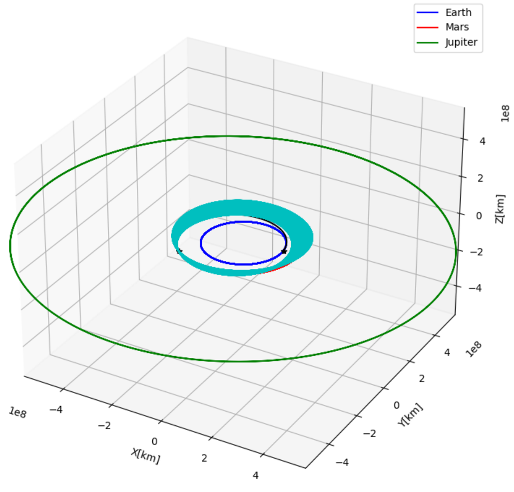


- ○ Velocity after swing-by to Sun = $\boldsymbol{V}_{\infty O}$ + Velocity of celestial body for swing-by to Sun
  → Keplerian elements to Sun
  → apoapsis altitude < orbital radius of Europa and Enceladus → OK!

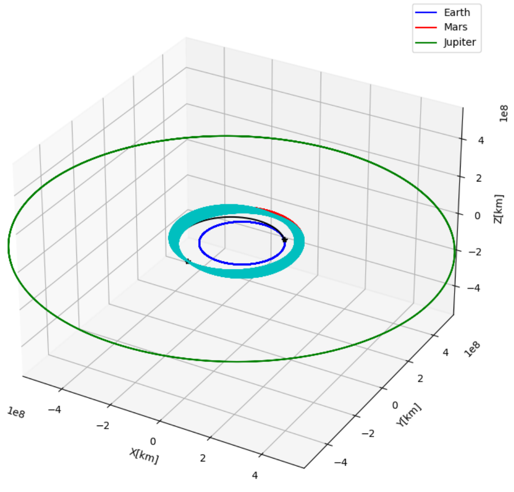
Energy Analysis / Outbound

○ Outbound: Mars Swing-by

2024



2026



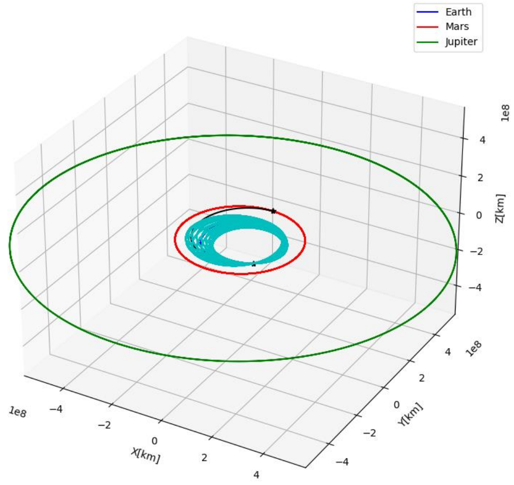
[deg]	2024	2026
0	233936000	227004000
20	233938000	226767000
40	234194000	227648000
60	236592000	233647000
80	246120000	242623000
100	261990000	251840000
120	277704000	259797000
140	289160000	265441000
160	**294193000**	**268102000**
180	292281000	267533000
200	284457000	263920000
220	272898000	257843000
240	260305000	250188000
260	249218000	242072000
280	241275000	234750000
300	236702000	229484000
320	234652000	227037000
340	234019000	226766000

In all cases, the mean orbital radius of Jupiter (= about 778,000,000 km) is not reached

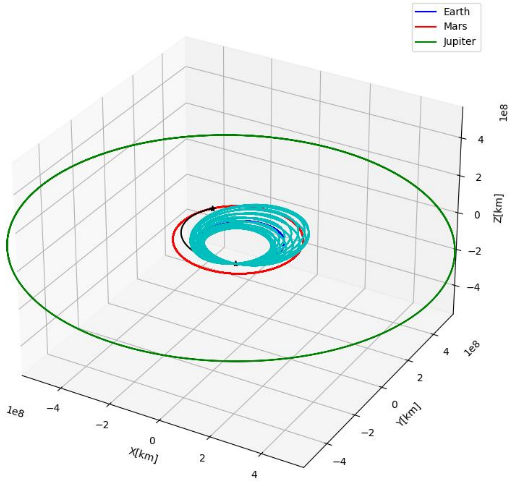
Energy Analysis / Inbound

○ Inbound: Earth Swing-by

2024



2026



[deg]	2024	2026
0	204388000	156753000
20	194424000	158470000
40	179984000	160424000
60	165384000	164171000
80	155698000	177551000
100	152202000	205876000
120	151804000	237682000
140	152531000	262957000
160	153555000	**273637000**
180	154454000	266110000
200	154970000	243286000
220	154957000	212388000
240	154375000	181118000
260	153677000	158329000
280	168793000	152369000
300	187068000	152299000
320	200709000	153466000
340	**206860000**	155051000

In all cases, the mean orbital radius of Jupiter (= about 778,000,000 km) is not reached

Thank you