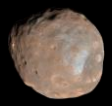

AAS 19-389

Science Orbits Design for the Lunar CubeSat EQUULEUS and for the Phobos Sample Return Mission MMX

Takuya Chikazawa — The University of Tokyo, Japan.

Nicola Baresi — Institute of Space and Astronautical Science/JAXA, Japan.

Naoya Ozaki — Institute of Space and Astronautical Science/JAXA, Japan.

Stefano Campagnola — Jet Propulsion Laboratory/California Institute of Technology, US.

Yasuhiro Kawakatsu — Institute of Space and Astronautical Science/JAXA, Japan.

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Government sponsorship acknowledged.

Introduction

Background

Dominant Parameters for Eclipse Problem

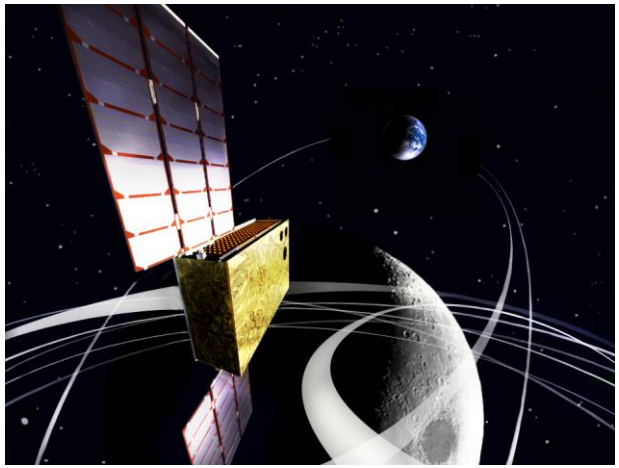
Application

Conclusion

Overview of Two Upcoming Spacecraft

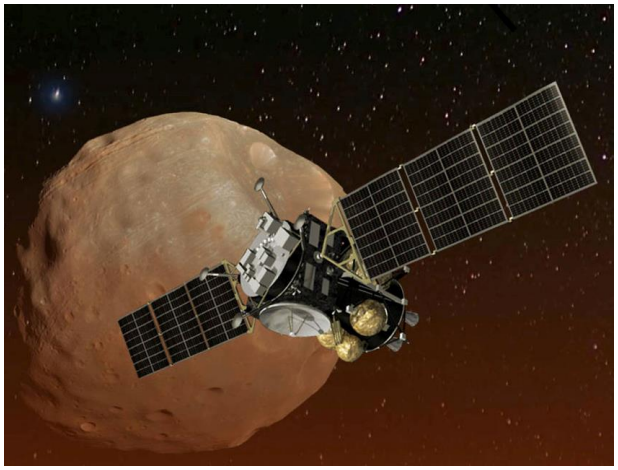
EQUULEUS

(EQUilibriUm Lunar-Earth point 6U Spacecraft)



MMX

(Martian Moons eXploration)

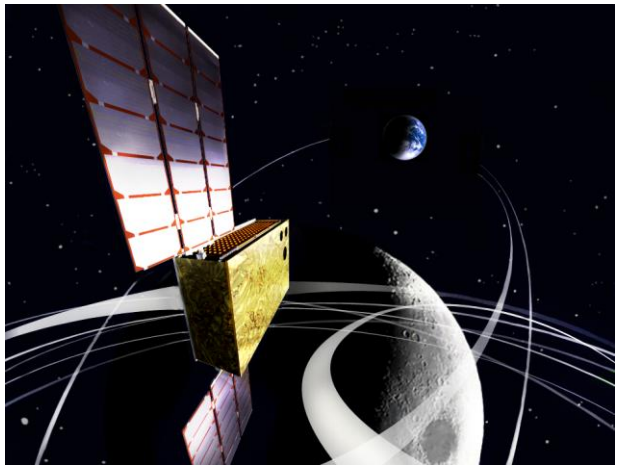


University of Tokyo/JAXA	Operator	JAXA
2019	Launch	2024
Earth-Moon Quasi-halo Orbit	Target Orbit	Mars-Phobos QSO
Observe Lunar Impact Flash	Science Mission	Sample Return from Phobos
6U CubeSat, Student Project	Characteristic	First Martian Round-trip

Overview of Two Upcoming Spacecraft

EQUULEUS

(EQUilibriUm Lunar-Earth point 6U Spacecraft)



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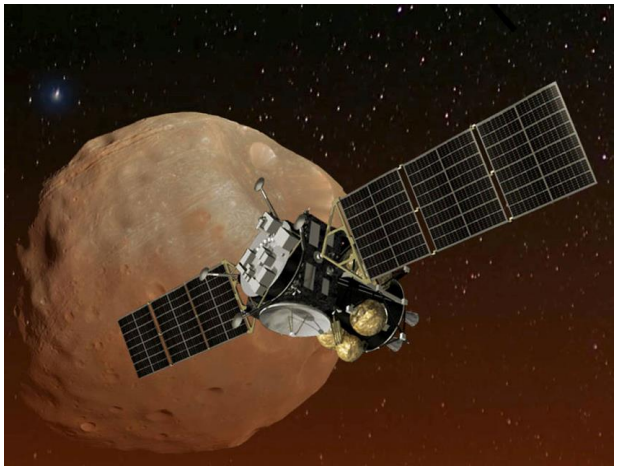


Periodic Orbits in Three-body System

Earth-Moon Quasi-halo Orbit	Target Orbit	Mars-Phobos QSO

Remain in the vicinity of a target body for long span

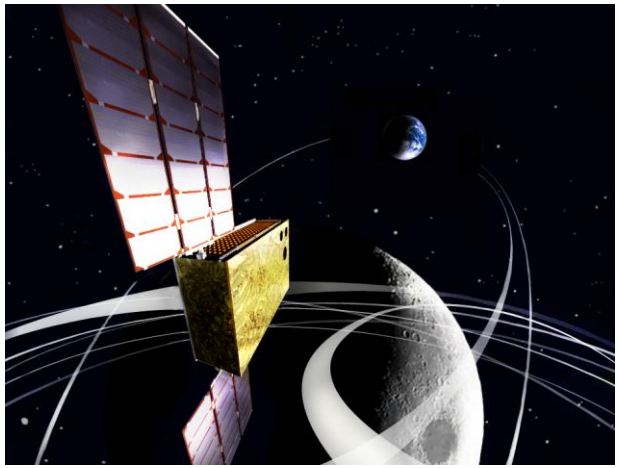
- Power Budget, Thermal Control

→ **Eclipse Problem**

Overview of Two Upcoming Spacecraft

EQUULEUS

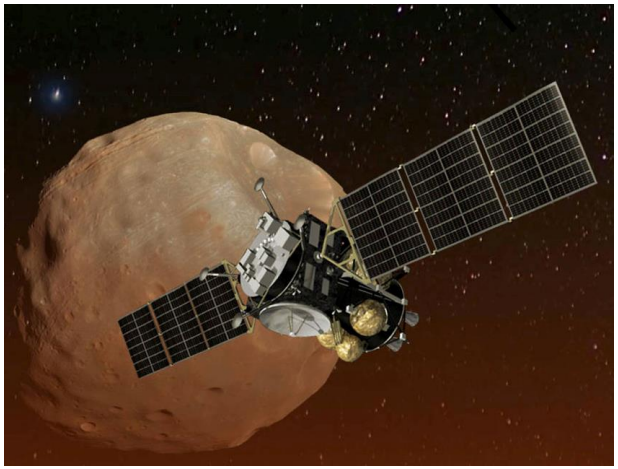
(EQUilibriUm Lunar-Earth point 6U Spacecraft)



Found unacceptable long eclipses
(CubeSat)

MMX

(Martian Moons eXploration)



Found eclipses
(≥3500 kg Class)

Eclipse of periodic orbit in three-body system
→ General problem for space exploration

What do we propose ?

- Establish systematic techniques to deal with eclipses in three-body systems
  - reveal general structure of eclipse events
  - dive into properties of synodic resonant periodic orbits (Zimovan, et al., 2017)

- Apply these methods to the two real missions, which are heading to periodic orbits in three-body systems

Introduction
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Dominant Parameters for Eclipse Problem
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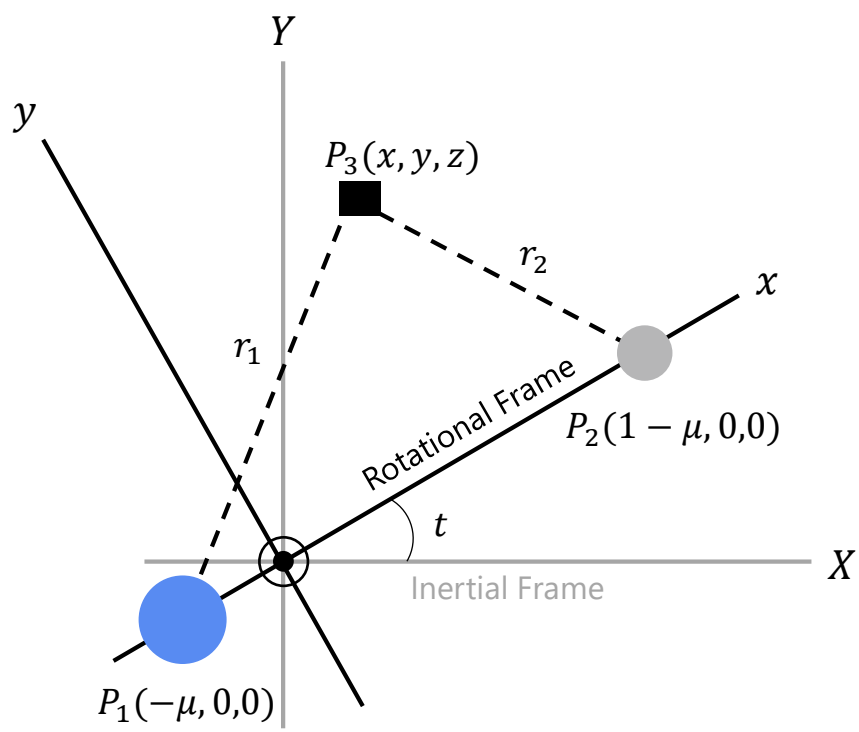
Circular Restricted Three Body Problem (CR3BP)

Conventional model for the trajectory design in the three-body systems

Assuming that

1. The mass of three body satisfy $m_{P1} > m_{P2} \gg m_{P3}$
2. P_1 and P_2 move in circular orbits about their barycenter



$$\ddot{x} - 2\dot{y} = \frac{\partial U^*}{\partial x}$$

$$\ddot{y} + 2\dot{x} = \frac{\partial U^*}{\partial y}$$

$$\ddot{z} = \frac{\partial U^*}{\partial z}$$

where

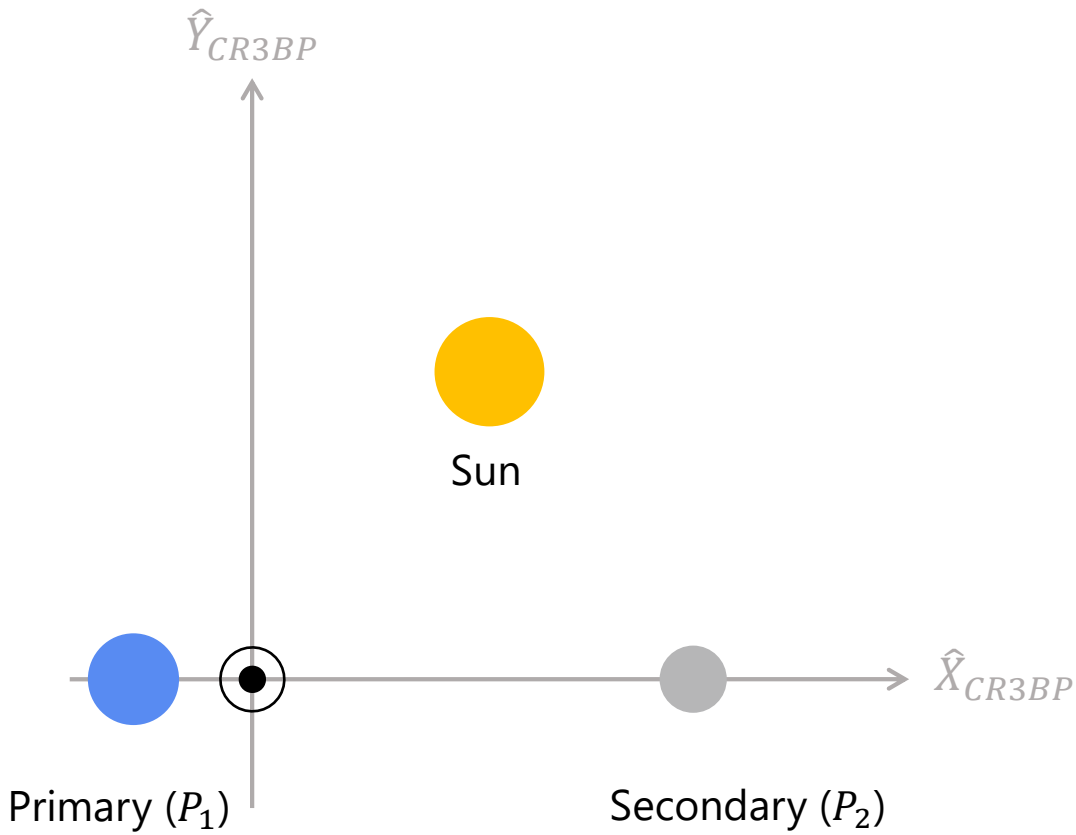
$$U^* = \frac{1-\mu}{r_1} + \frac{\mu}{r_2} + \frac{1}{2}(x^2 + y^2)$$

$$\mu = \frac{m_{P2}}{m_{P1} + m_{P2}}$$

Rotational Frames for Eclipse Analysis

Define two **Sun direction fixed** rotational frames for visualization purposes

→ Shadow cone from the occulting body is fixed



Rotational Frames for Eclipse Analysis

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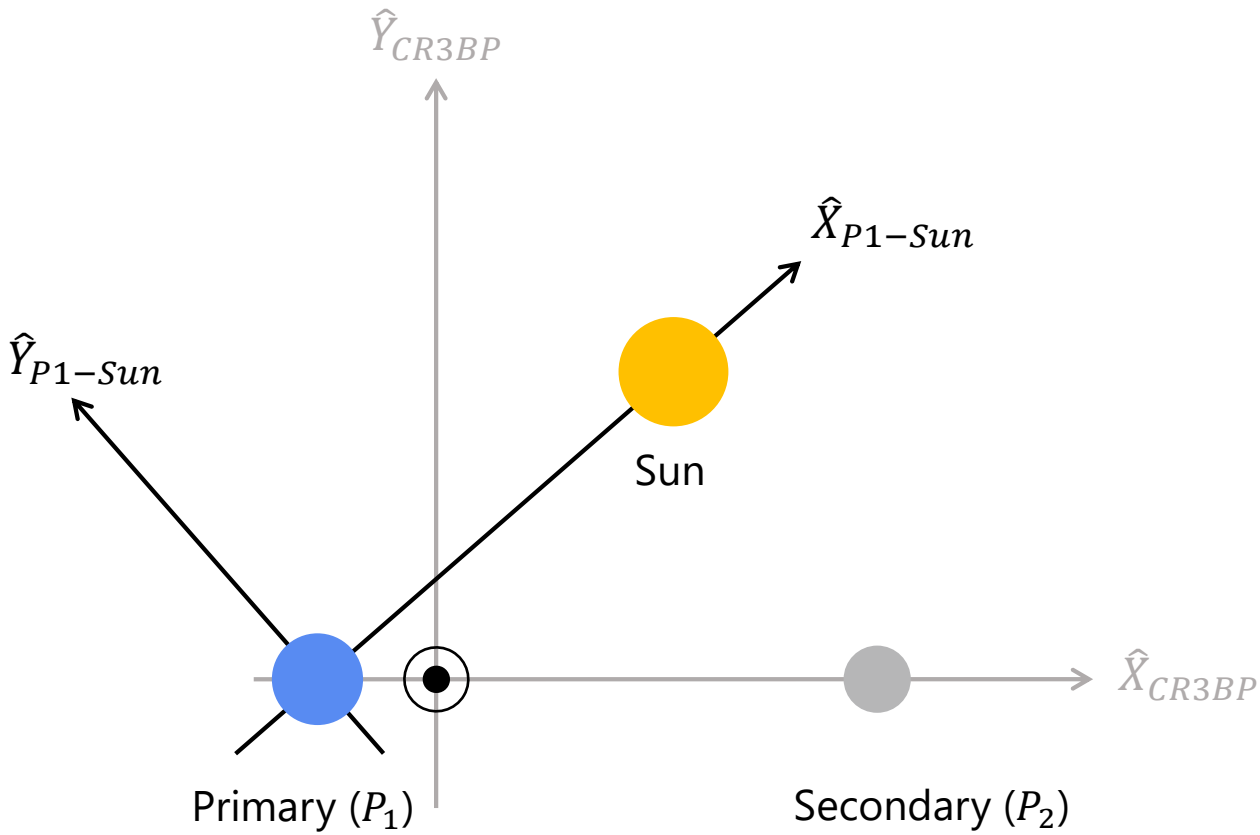

Rotational Frames for Eclipse Analysis

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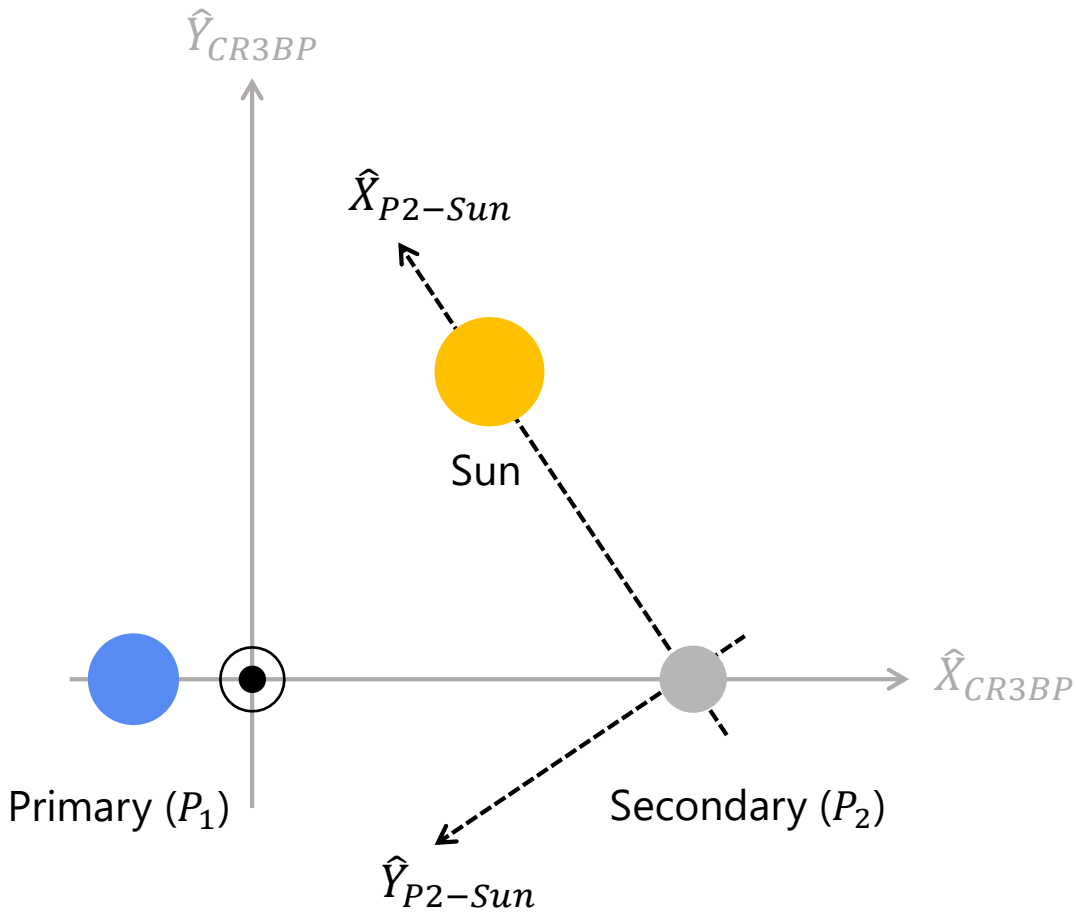
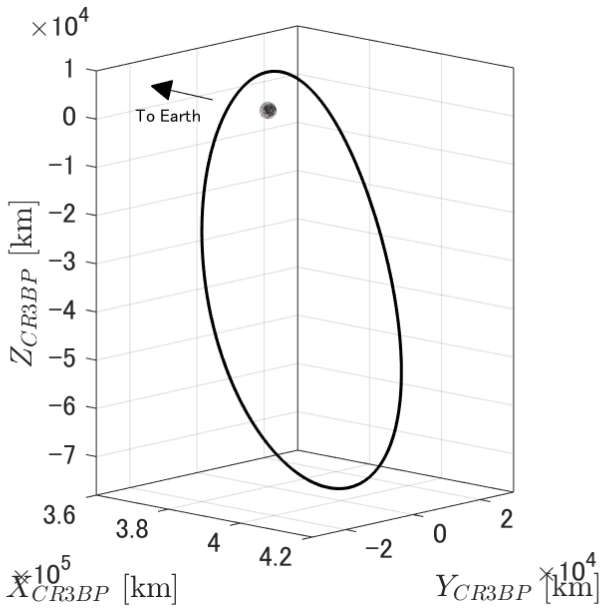


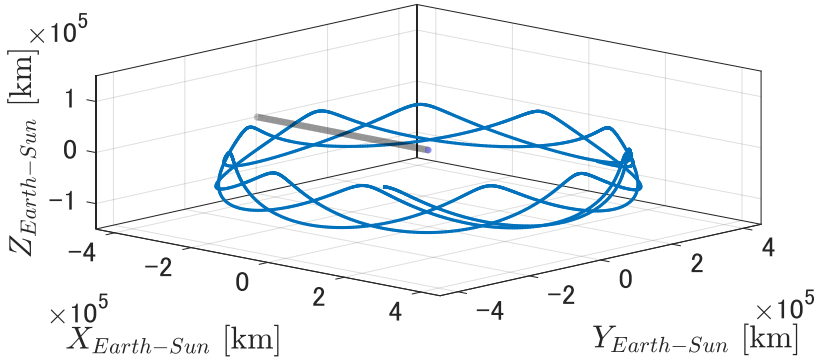
Rotational Frames for Eclipse Analysis

Ex) Earth-Moon halo orbit

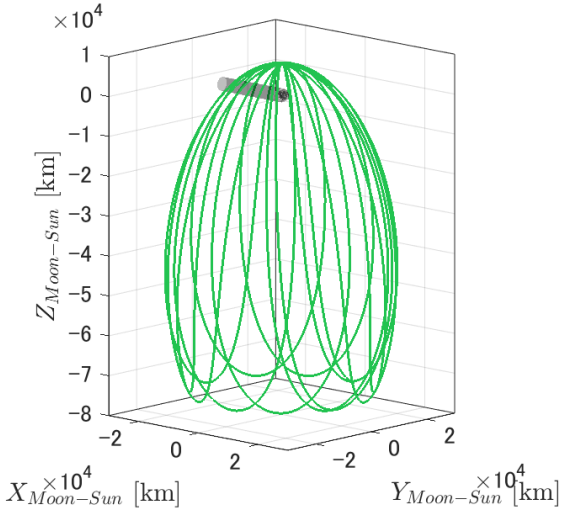
CR3BP



Earth-Sun Rotational frame

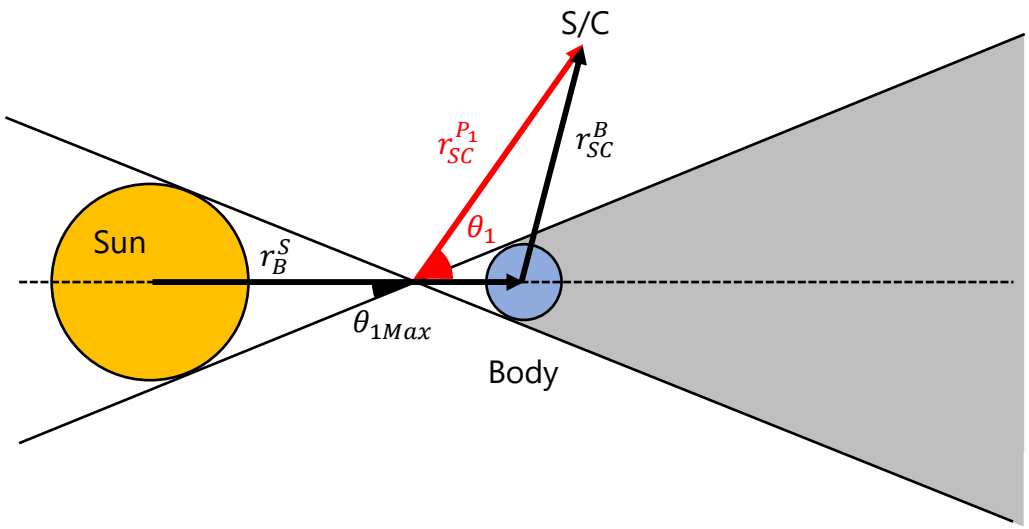


Moon-Sun Rotational frame



Eclipse Model

Conical Eclipse Model



$$\theta_1 = \cos^{-1}\left(\frac{r_{SC}^{P_1} \cdot r_B^S}{\left|r_{SC}^{P_1}\right|\left|r_B^S\right|}\right) \leq \theta_{1Max}$$

Eclipse

Introduction

Background

Dominant Parameters for Eclipse Problem

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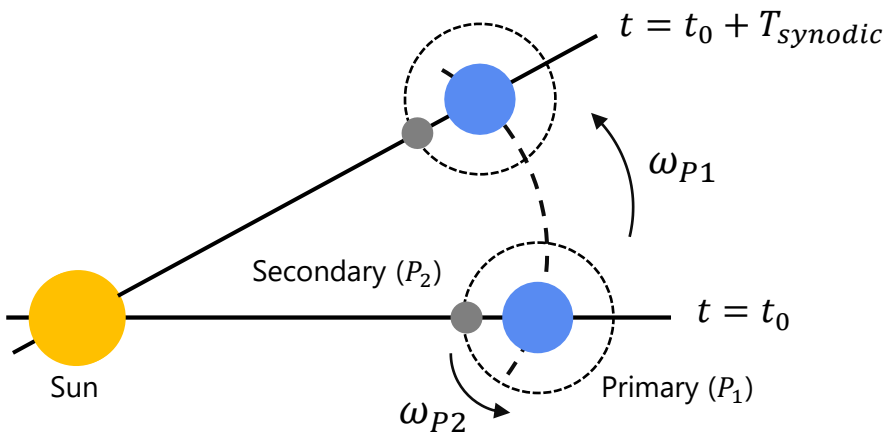
Conclusion

Synodic Period

The time elapsed between the Sun, the primary (P_1) and the secondary (P_2) find themselves in **the same relative configuration**



$$T_{Synodic} = \frac{2\pi}{\omega_{P2} - \omega_{P1}} \qquad \text{(In CR3BP)}$$

Synodic Ratio

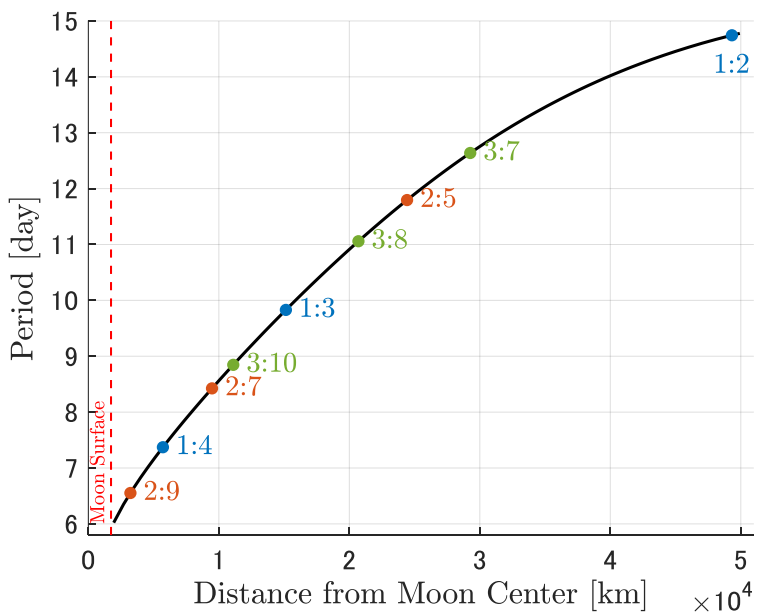
The period of orbit T_{PO} is resonant with $T_{Synodic}$

→ **Synodic Resonant Periodic Orbit** (Zimovan, et al., 2017)

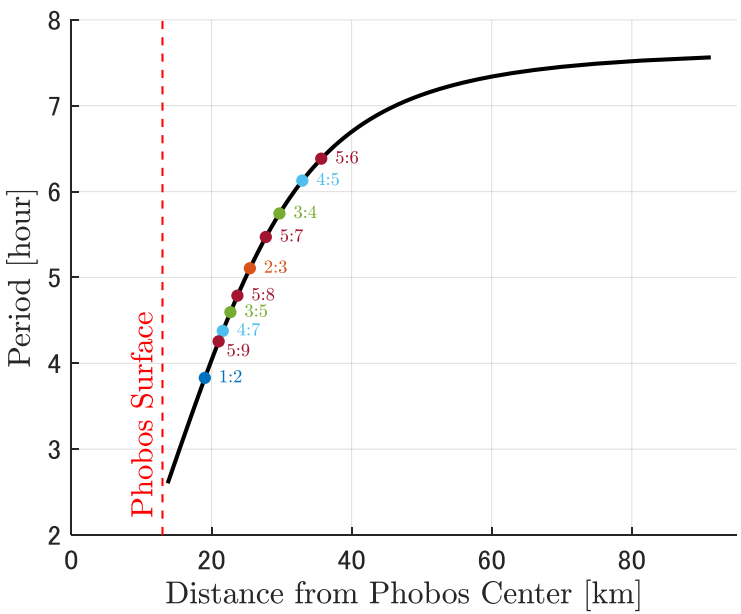
$$T_{Synodic} : T_{PO} = n : m$$

Orbit completes n revolutions during m synodic periods

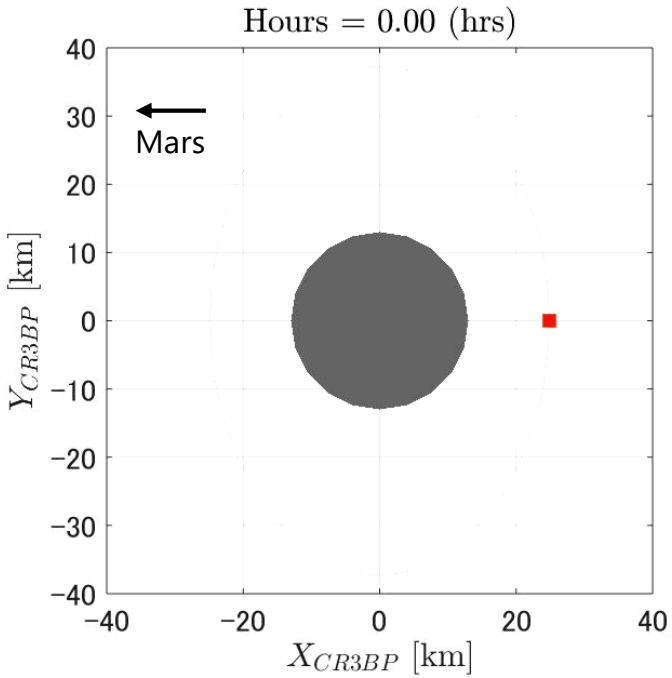
Earth-Moon Synodic Resonant Halo Orbit

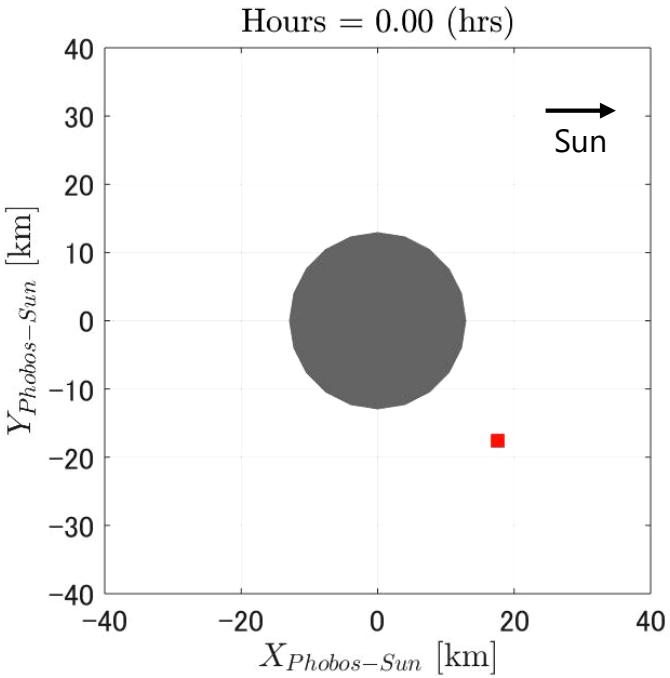


Mars-Phobos Synodic Resonant QSO

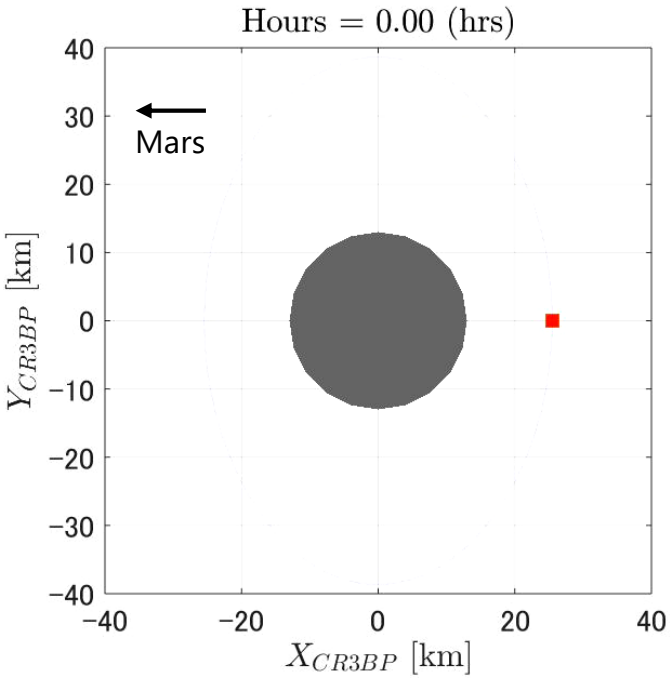


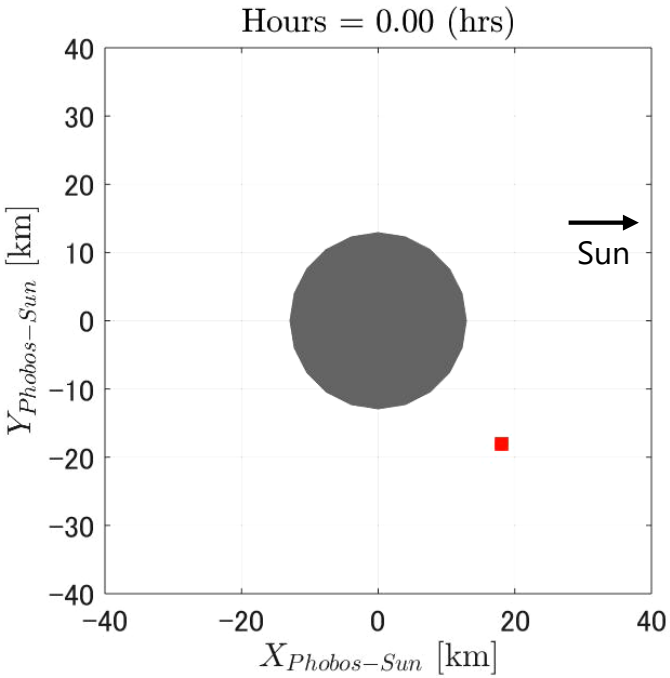
Non-Synodic Resonant QSO





Synodic Resonant QSO

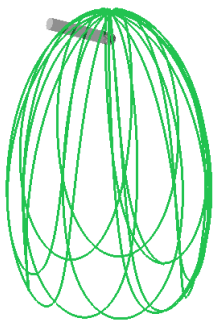




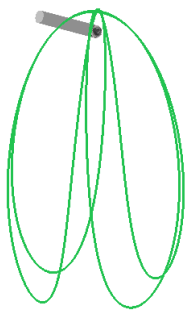
Synodic Resonant Periodic Orbits

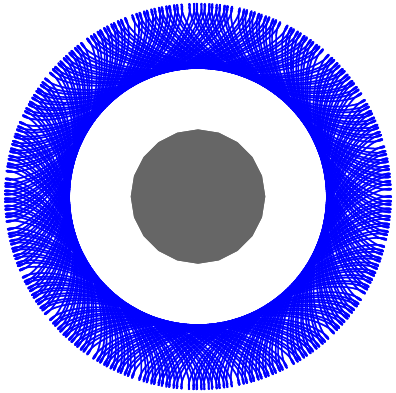
Non-Synodic Resonant Periodic Orbit

Synodic Resonant Periodic Orbit

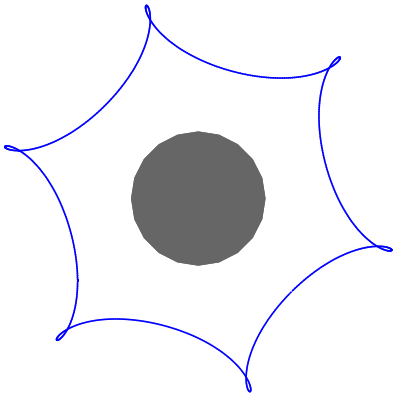


halo Orbit





QSO

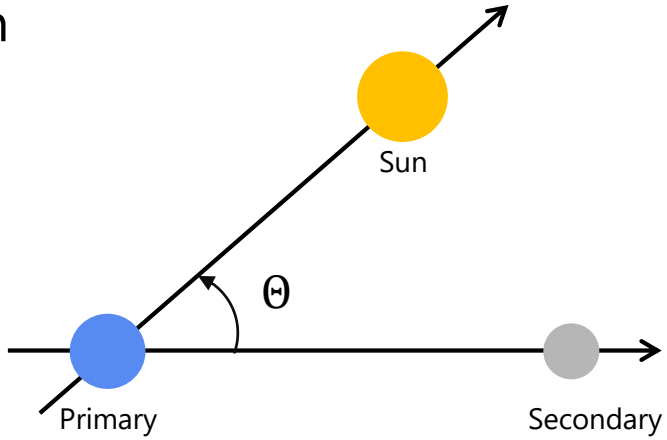


Synodic resonant periodic orbits **repeat their shape** in Sun-fix frame

→ all eclipses can be detected with short orbital propagations

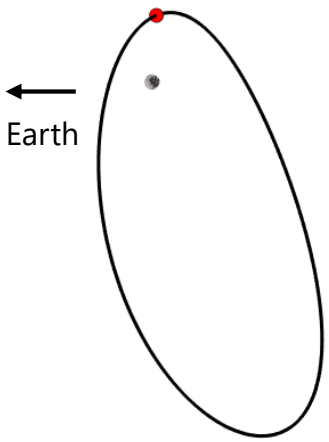
Elongation Angle (Sun-Primary-Secondary Angle)

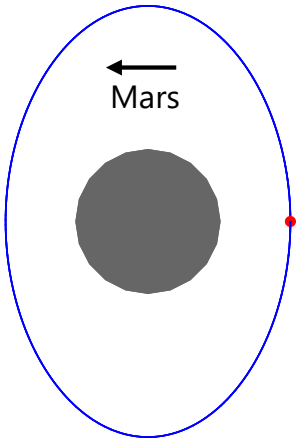
Elongation angle frames the geometry of planets with respect to the Sun



We define the initial elongation angle as Θ_0

- Halo orbit → Initial perilune
- QSO → Initial anti-Mars direction

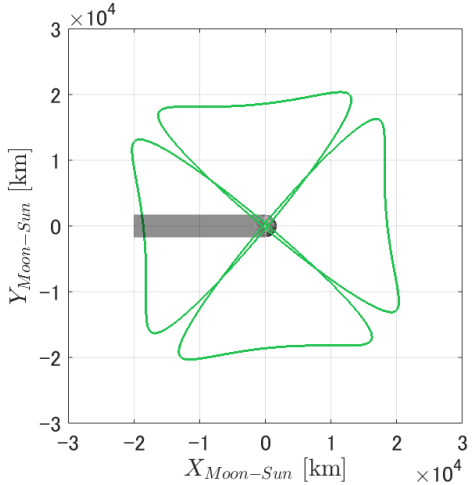




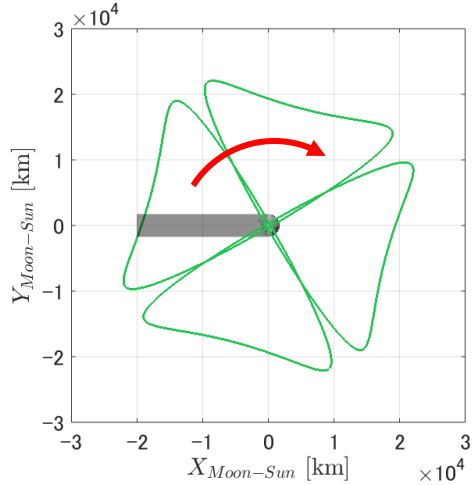
Elongation Angle

Seen from polar direction

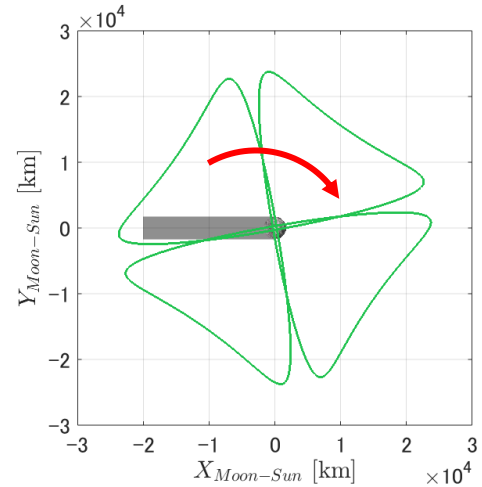
$\Theta_0 = 40$



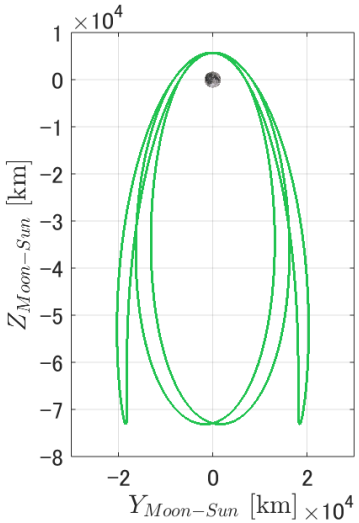
$\Theta_0 = 60$

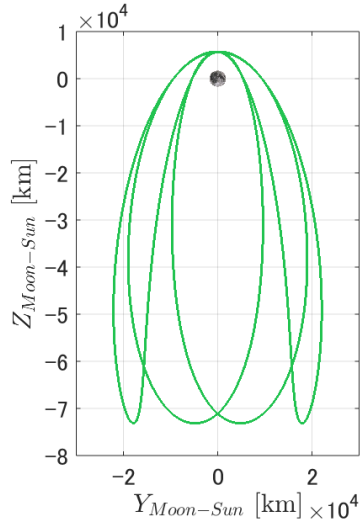


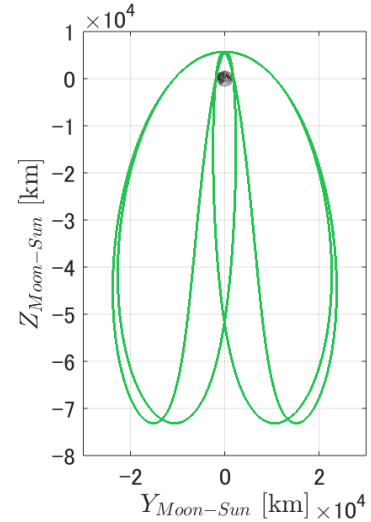
$\Theta_0 = 80$



Seen from anti-Sun direction

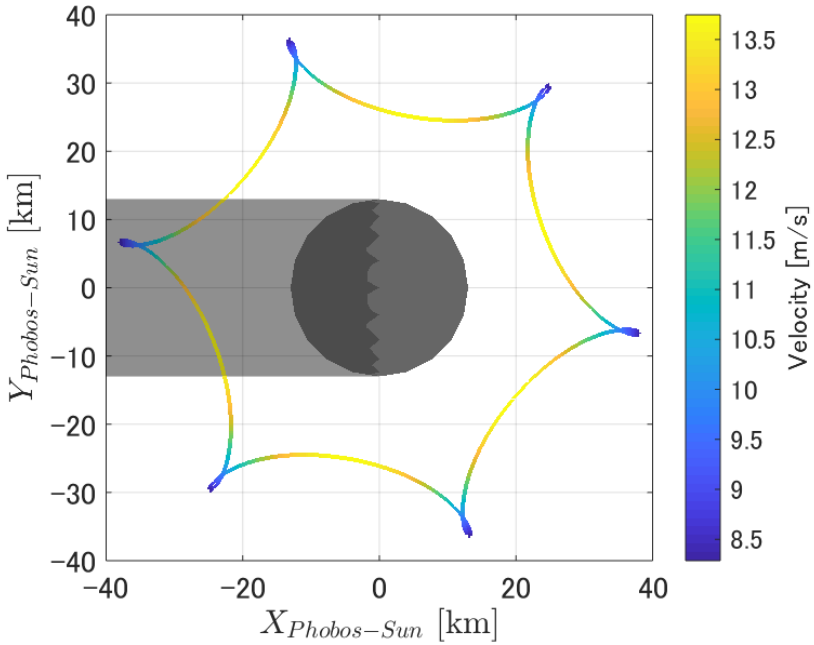




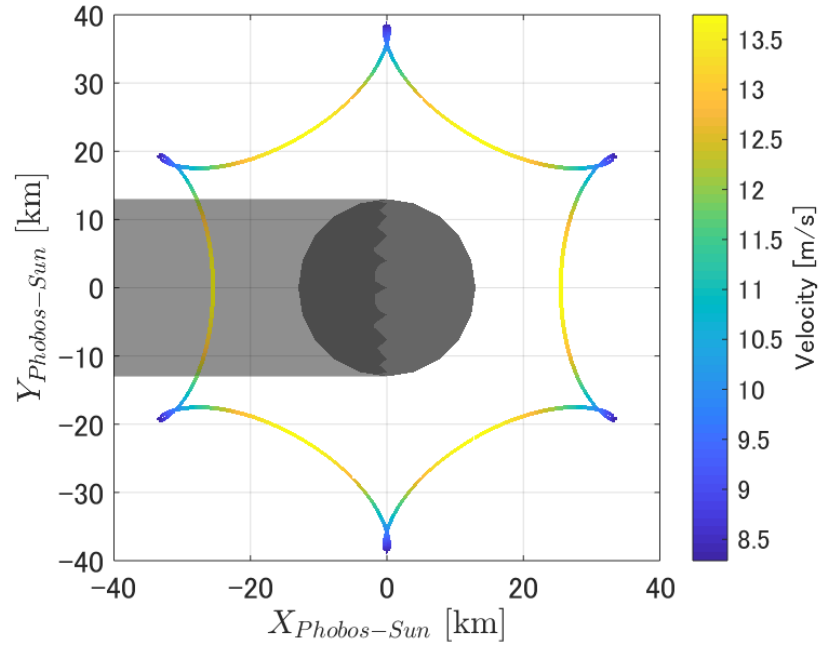


Elongation Angle

$\Theta_0 = 40$



$\Theta_0 = 60$



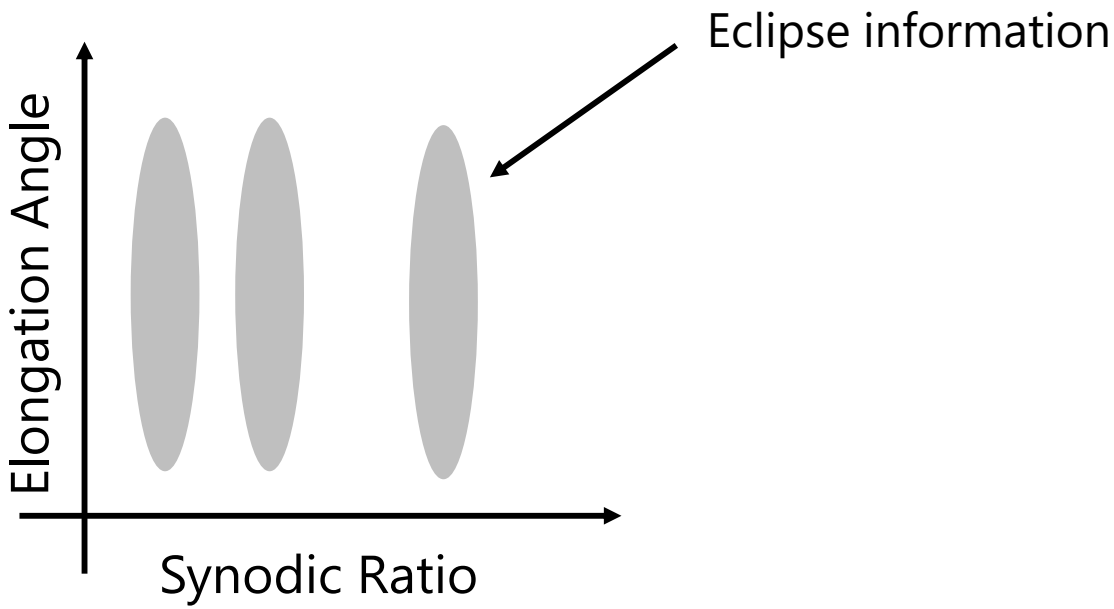
Initial elongation angle: Θ_0 determines eclipse relations

→ Changing this parameter, we can avoid/minimize eclipse

Eclipse Map

Dominant parameters for eclipse minimization

➡ **Synodic Ratio** and **Elongation Angle**



Introduction

Background

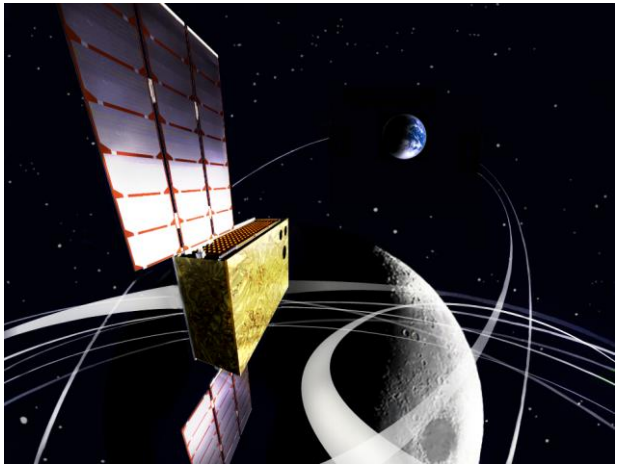
Dominant Parameters for Eclipse Problem

Applications

Conclusion

Application Ⅰ

EQUULEUS



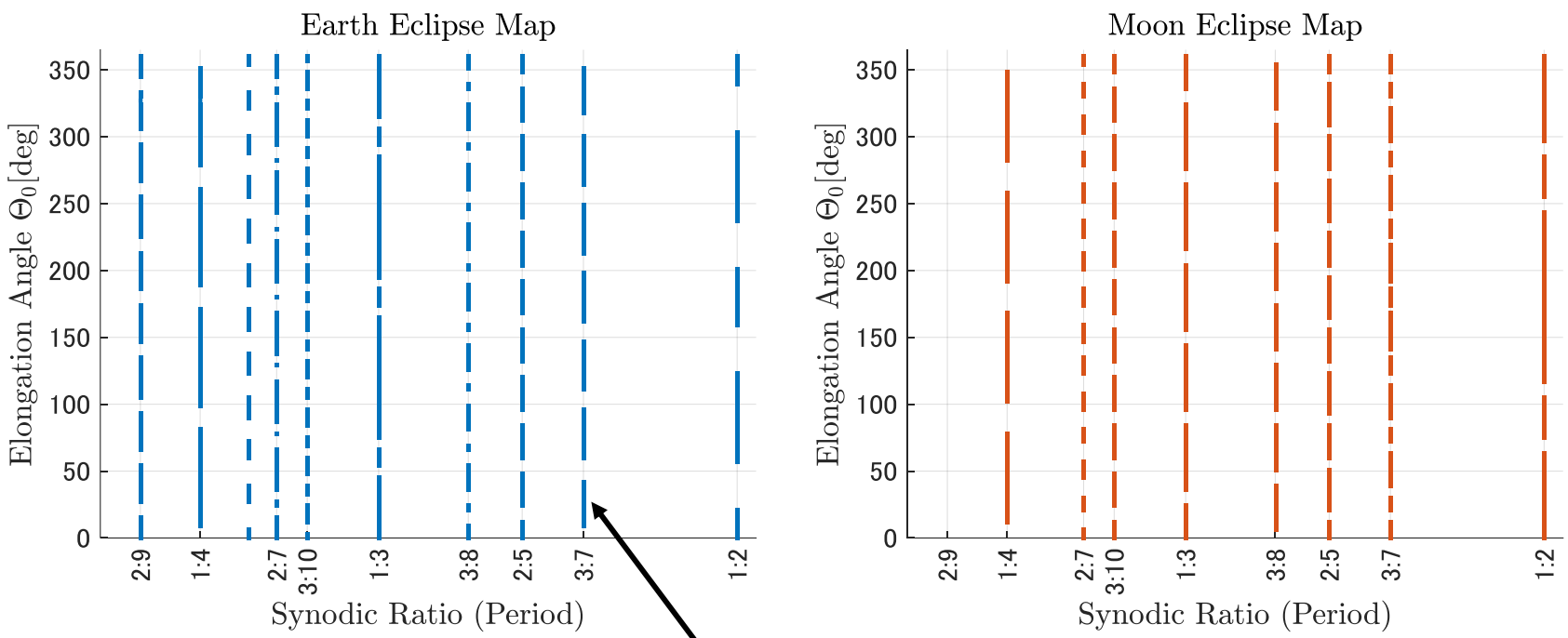
6U class CubeSat

Earth-Moon quasi-halo orbit

Eclipse constraint: Less than **30 min**

Application I

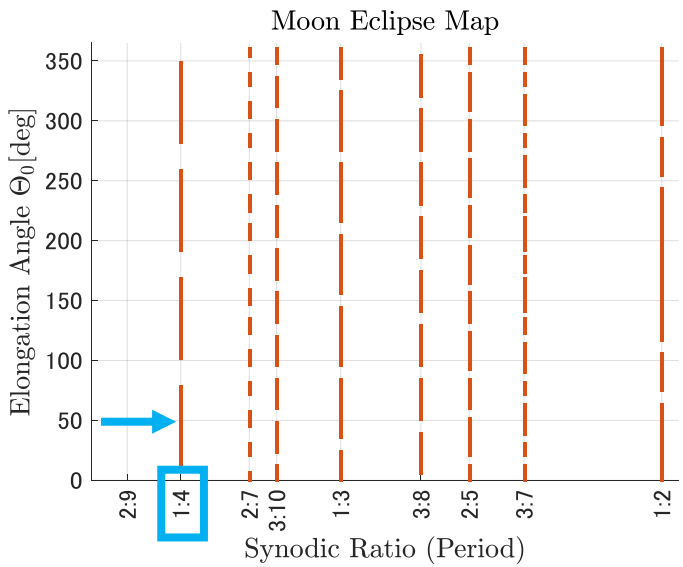
Eclipse Map of Earth-Moon halo Orbits

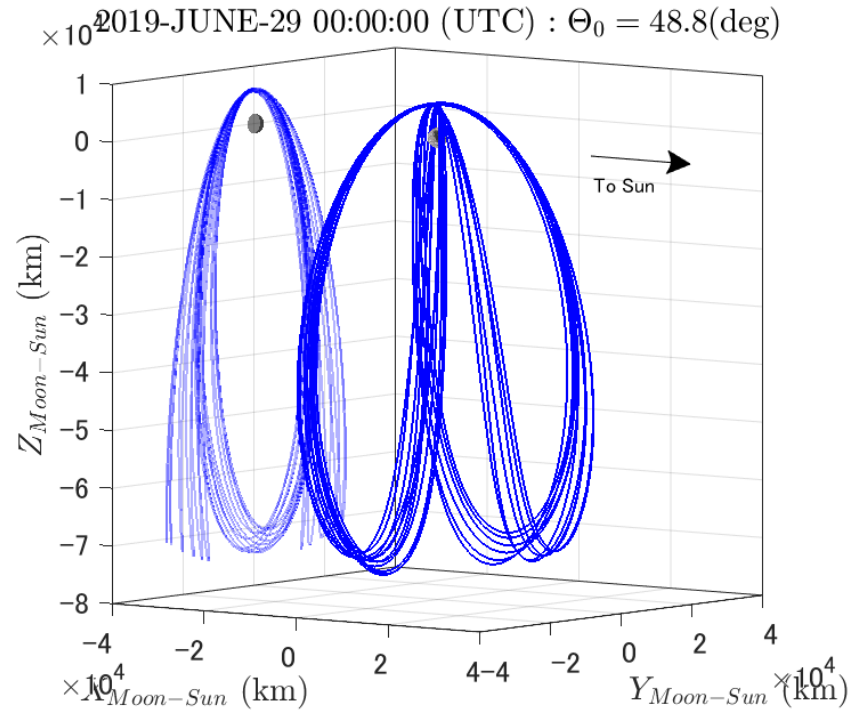


dots indicate eclipse-free halo orbits

Application I

Science Orbit Design with Eclipse Map





T_{PO} ≈7.37 (days)

1:4

2019-JUNE-29 00:00:00 (UTC)

$\Theta_0 \approx 48.8$

Eclipse Map

Select Period (Synodic Ratio)

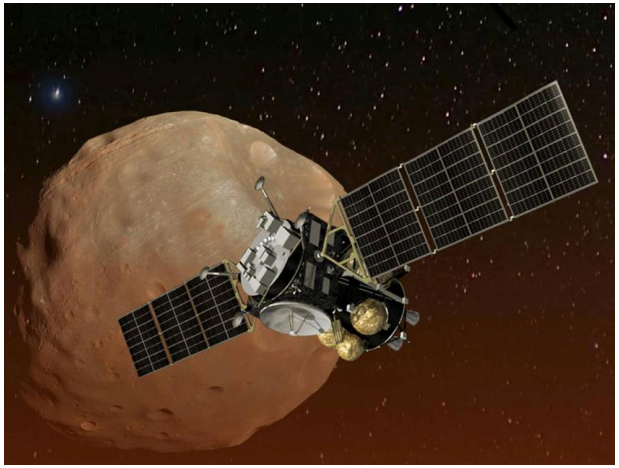
Select the epoch (Elongation : Θ_0)

Optimization

yields eclipse-free science orbit in full-ephemeris

Application Ⅱ

MMX



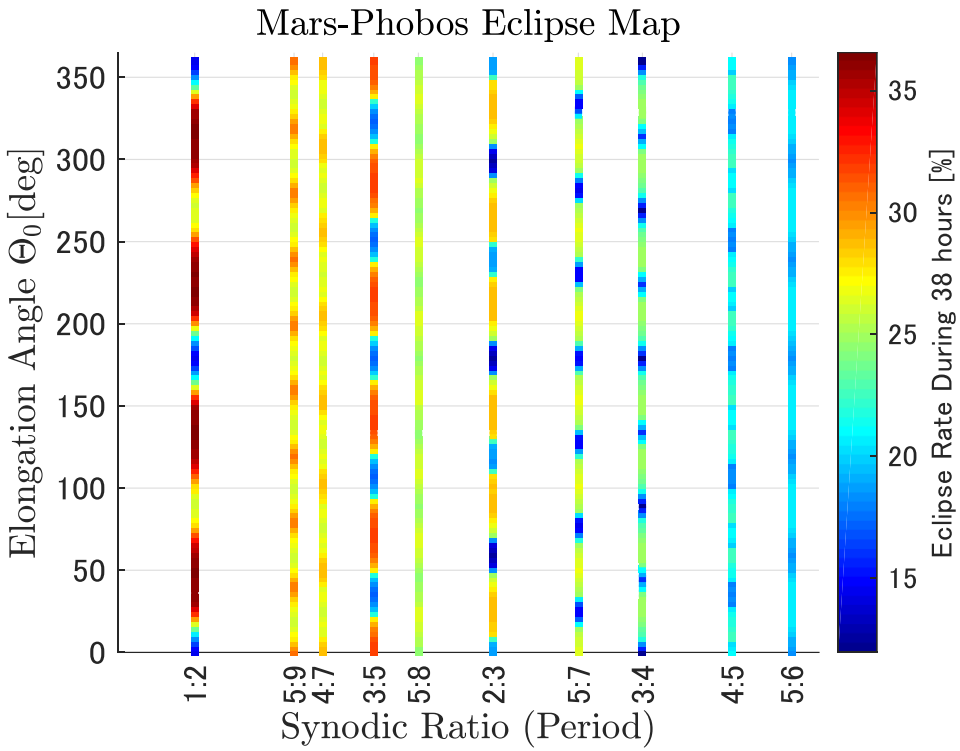
Sample Return Mission

Mars-Phobos Quasi-satellite orbit (QSO)

Eclipse constraint: **less than 3 hrs**

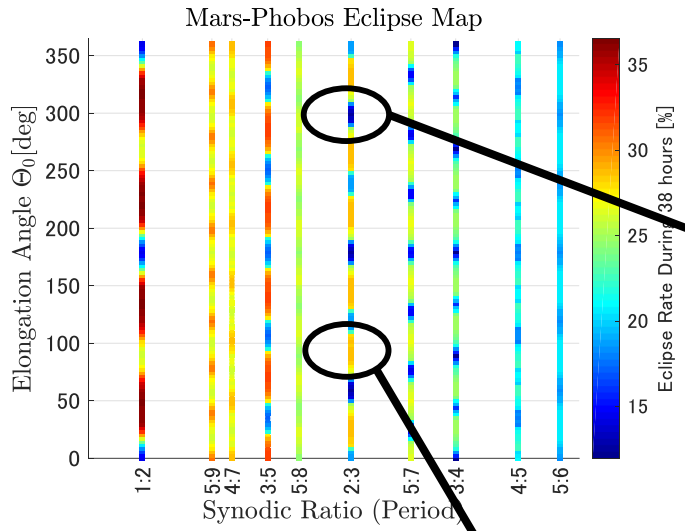
Application Ⅱ

Eclipse Map of Mars-Phobos Quasi-satellite Orbits (QSO)

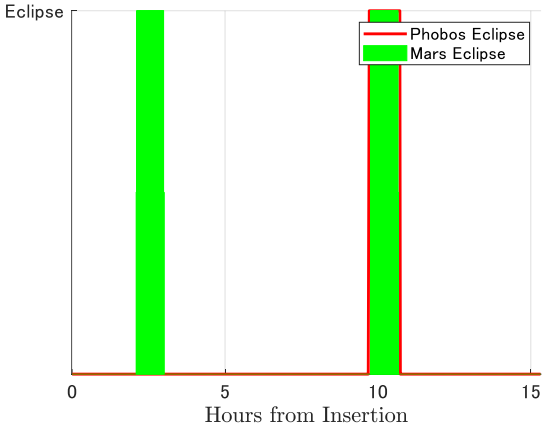


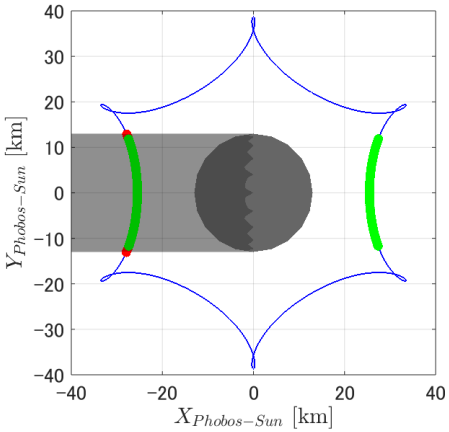
$$Eclipse\ Percentage\ [\%] = (Summation\ of\ Eclipse\ time)/(5 \times Synodic\ Period)$$

Application Ⅱ

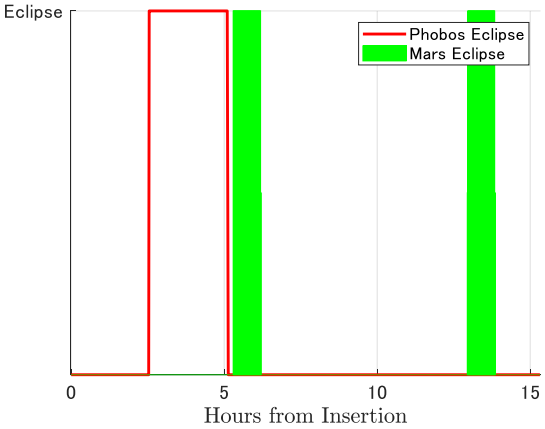


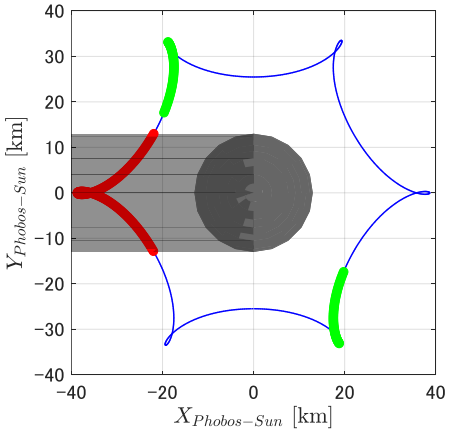
Minimum eclipse case





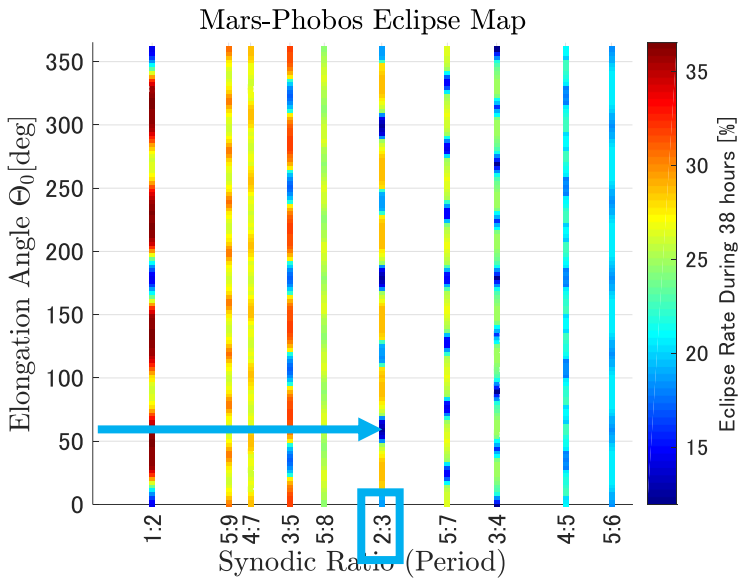
Maximum eclipse case

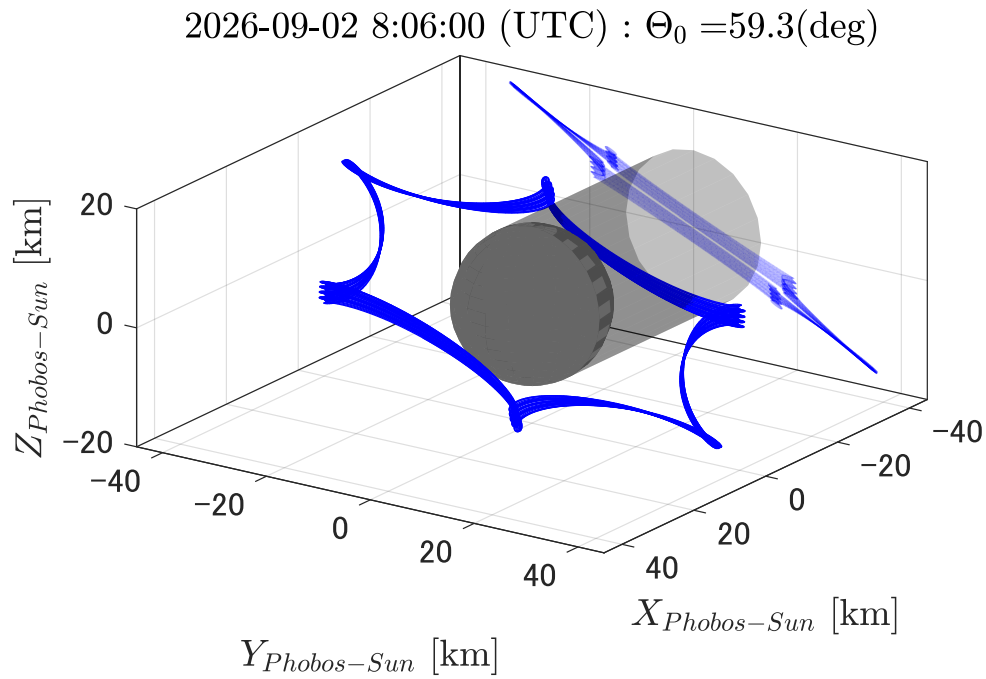




Application Ⅱ

Science Orbit Design with Eclipse Map





$T_{PO} \approx 5.1$ (hrs) 2:3

2026-Sep-02 8:06:00 (UTC) $\Theta_0 \approx 59.3$

Eclipse Map → Select Period (Synodic Ratio) → Select the epoch (Elongation : Θ_0) → Optimization

yields minimum-eclipse science orbit in full-ephemeris

Conclusion

- Identified dominant parameters for eclipse minimization

- Introduced a new concept for periodic orbits in three-body systems: *Eclipse Maps*

- Used eclipse maps to design science orbits of EQUULEUS and MMX in full-ephemeris models

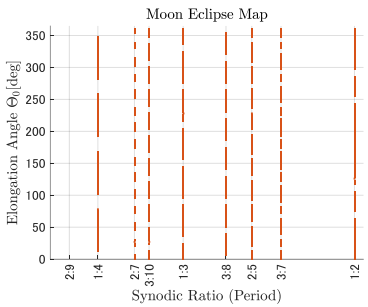
Summary

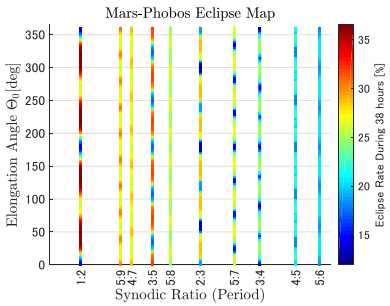
AAS 19-389

Science Orbits Design for the Lunar CubeSat EQUULEUS and for the Phobos Sample Return Mission MMX

(Motivation) Eclipse problem in three-body systems

(Contribution) Identifying key parameters, **synodic ratio** and **elongation angle** and proposing **Eclipse Map** for **Synodic Resonant Periodic Orbits**





(Result) Designing science orbits for two spacecraft with Eclipse Map

Thank you for your attention ありがとうございます

東京大学 THE UNIVERSITY OF TOKYO

Takuya Chikazawa (c.takuya@ac.jaxa.jp)
Master student, The University of Tokyo, Japan.

Pre-Decisional Information – For Planning and Discussion Purposes Only