B-020

Attitude and Orbit Control in Solar Sails Formation Flight around Sun-Earth L_2 Point

32nd Workshop on JAXA - Astrodynamics and Flight Mechanics
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In recent years…

Telescopes **become large** in order to achieve **high resolution**

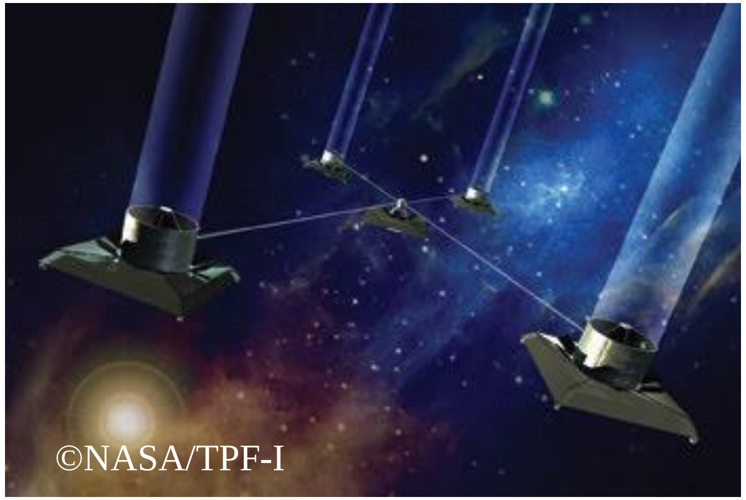
↳ Launching very large telescopes into space is impractical

→This problem can be solved by using an **interferometer**

◆ **Interferometer**

in space →

◆ **Formation flight**



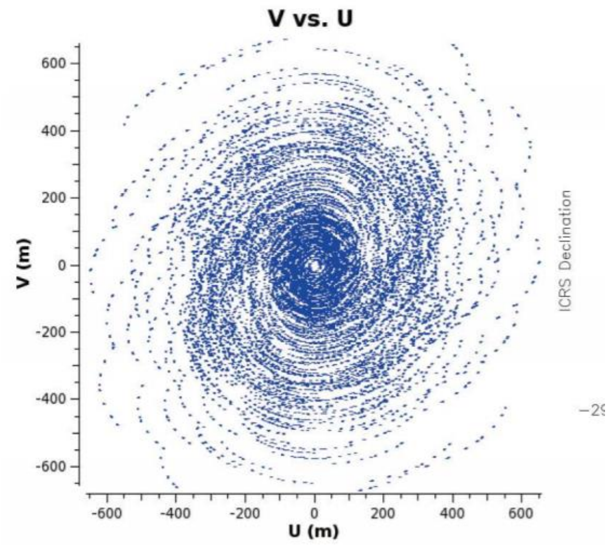
- The requirement of the interferometric observation

◆ *u*-*v* plane

Plot of

$$\frac{(\text{baseline vector } \mathbf{B})}{(\text{wavelength } \lambda)}$$

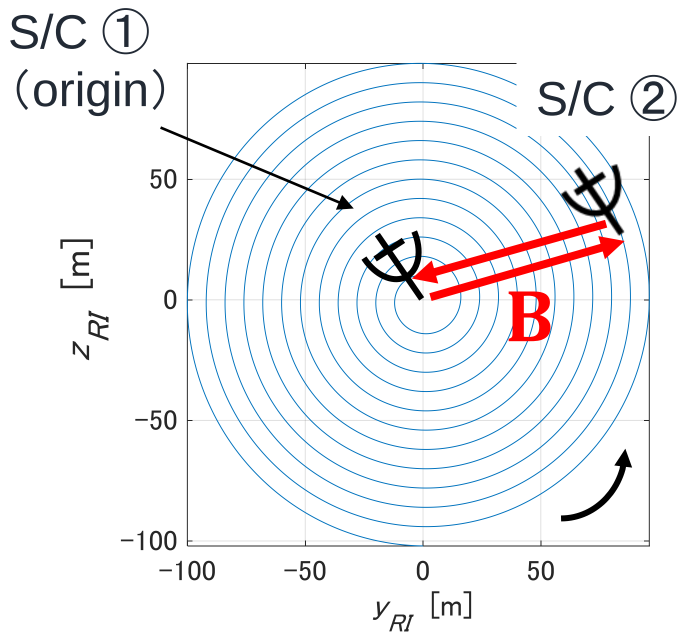
→ Fill in **broadly** and **densely**



u-*v* plane example

◆ Formation flight

➢ The vectors between the two satellites must be changed while observing



Relative orbit

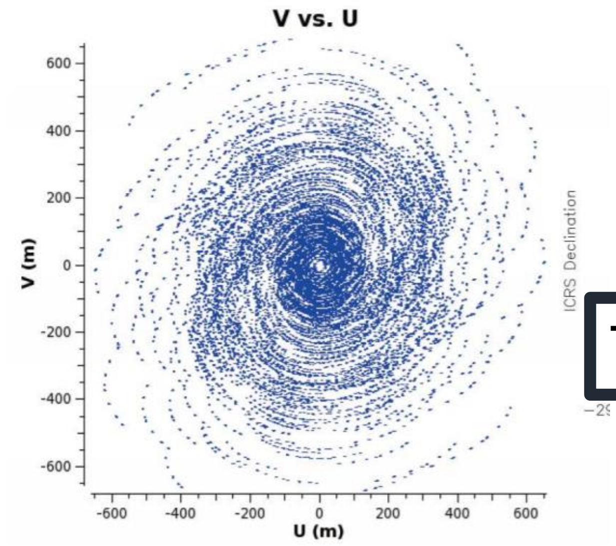
- The requirement of the interferometric observation

◆ *u*-*v* plane

Plot of

$$\frac{\text{(baseline vector } \mathbf{B}\text{)}}{\text{(wavelength } \lambda\text{)}}$$

→ Fill in **broadly** and **densely**



u-*v* plane example

◆ Formation flight

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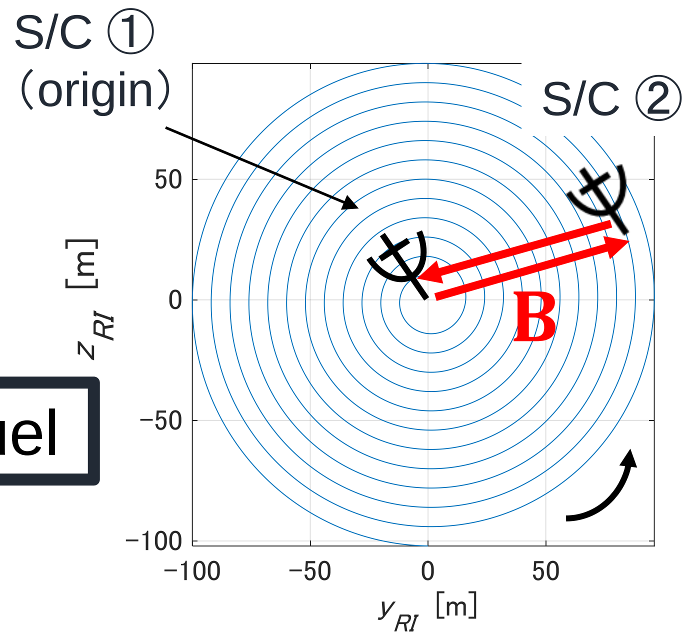


Relative orbit

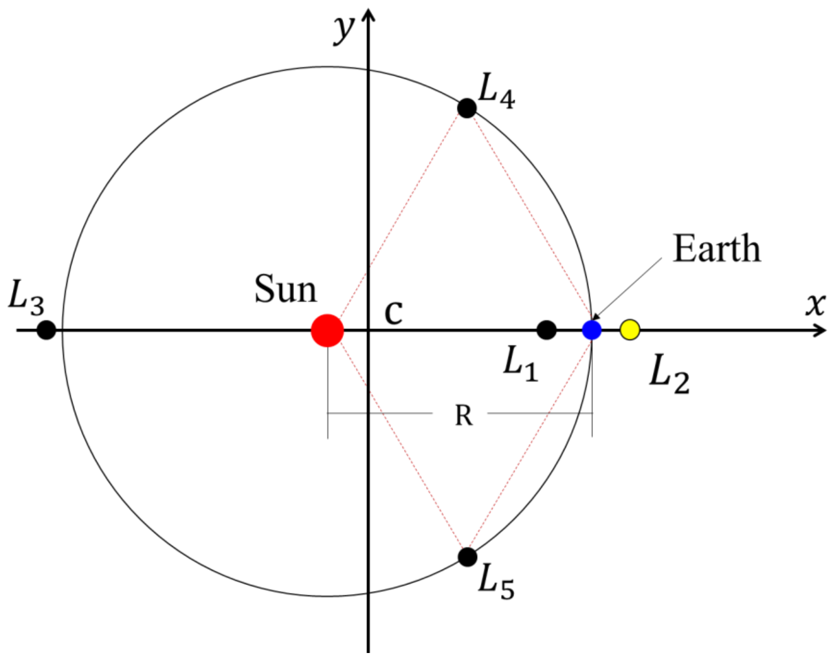
This process needs fuel

Introduction

We propose…

Fuel-free formation flying interferometric observation

- Perform around the **2nd Sun-Earth Lagrange point** for **solar sail** formation flight
  - Arbitrary orbits can be designed
  - **The orbit can be controlled with a small amount of control input**
- Control input is only **solar radiation pressure (SRP)**



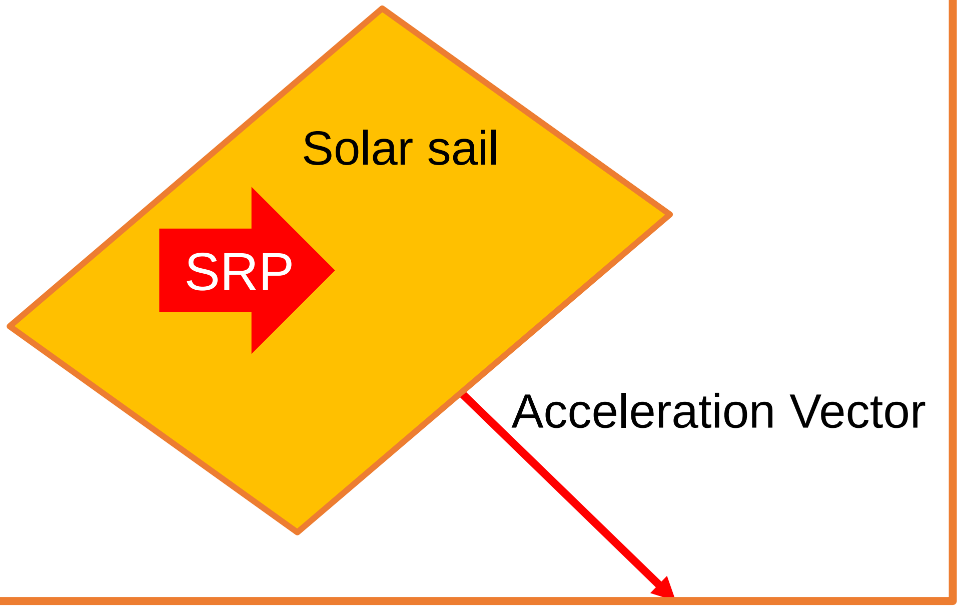
Lagrange point (Sun-Earth)

Solar Sail

◆ Orbit Control

- **Direction** of propulsive force
→Determined by **attitude**

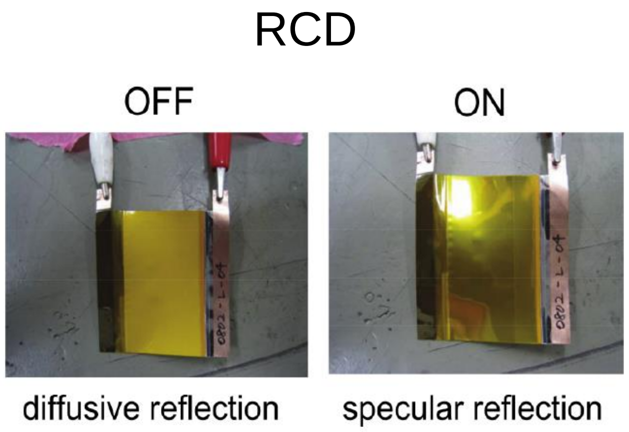
- **Magnitude** of propulsive force
→ determined by solar sail **size** (area and mass) and **surface optical properties**

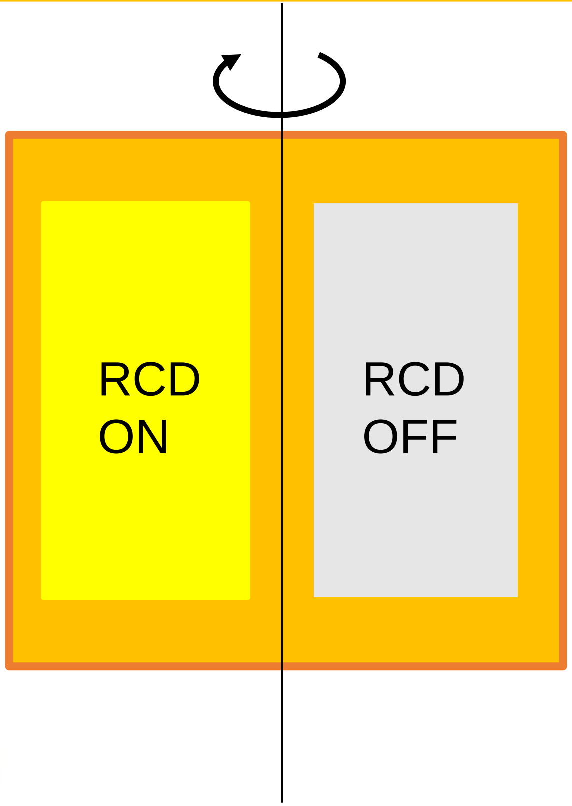


◆ Attitude Control

- **Attitude**
→ Controllable by generating **torque**

- **Torque**
→Controllable by **Reflected Control Device** (device that changes optical properties)

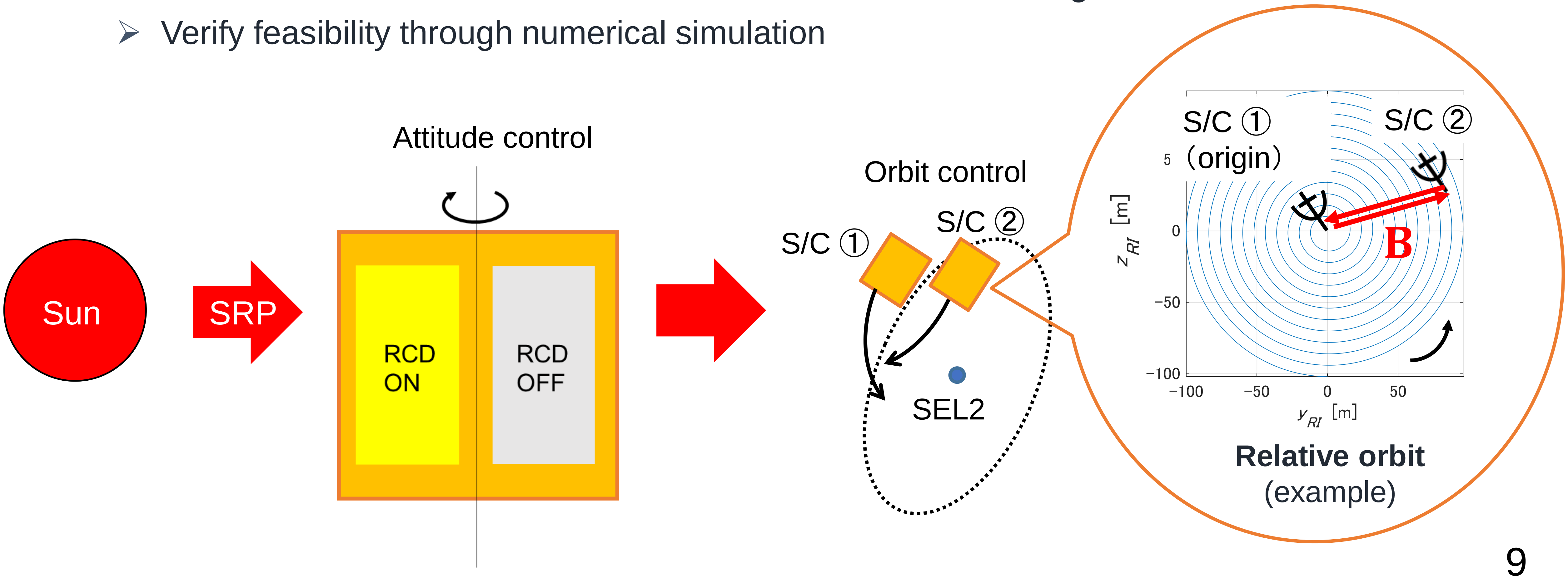




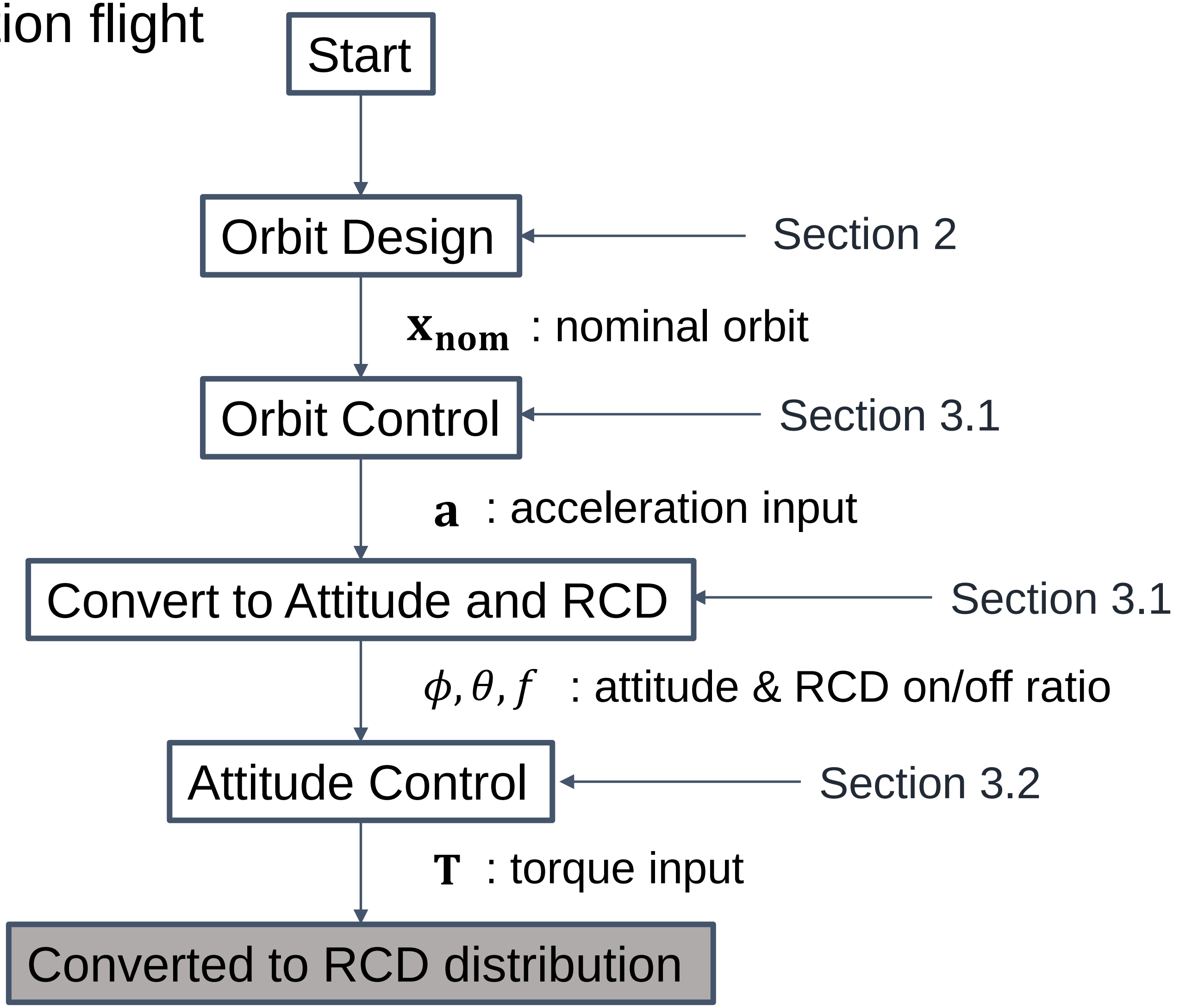
Purpose of this research

Completely **fuel-free formation flight interferometric observations** by simultaneous **orbit and attitude control** of solar sails using RCD

- Verify feasibility through numerical simulation



◆Flowchart of fuel-free formation flight



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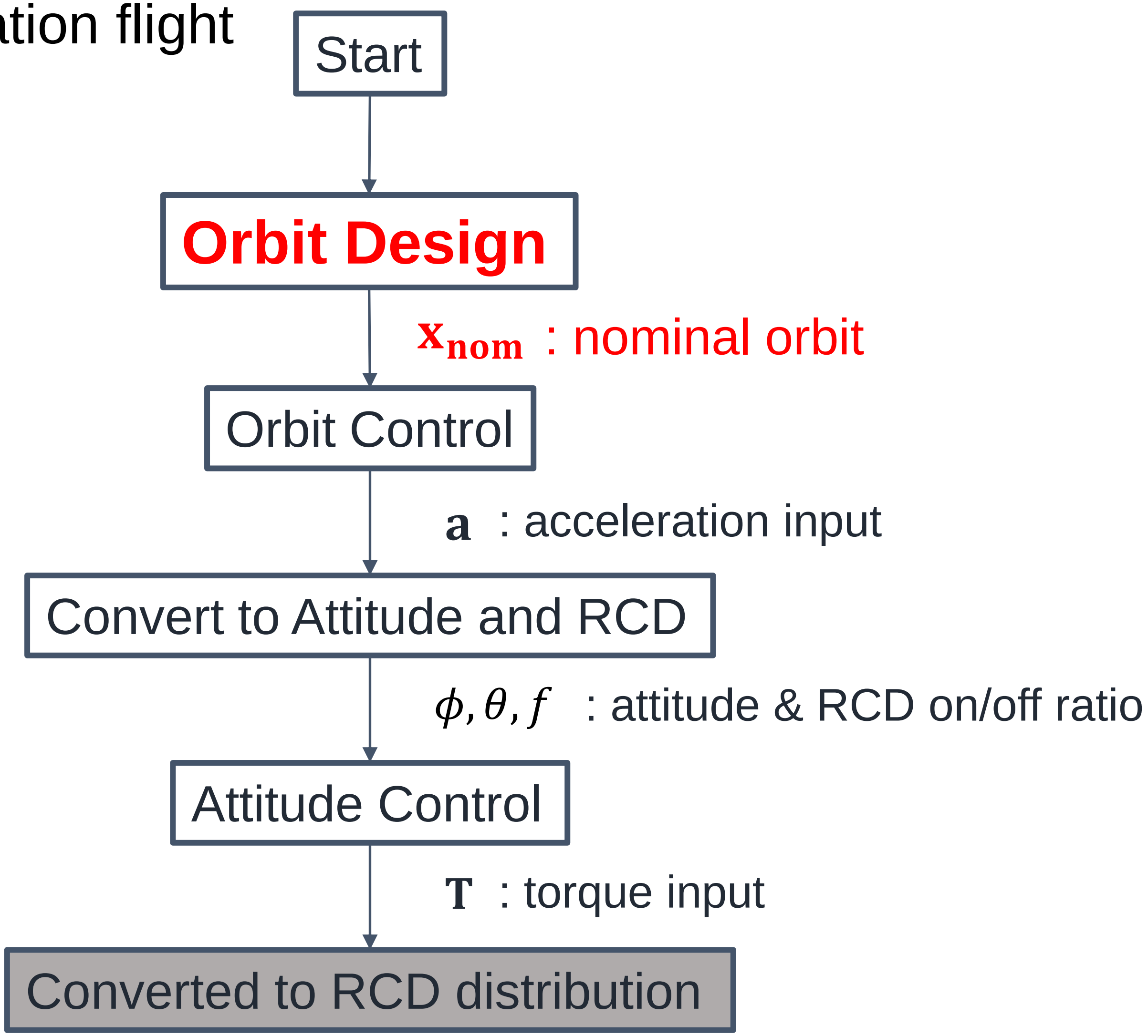
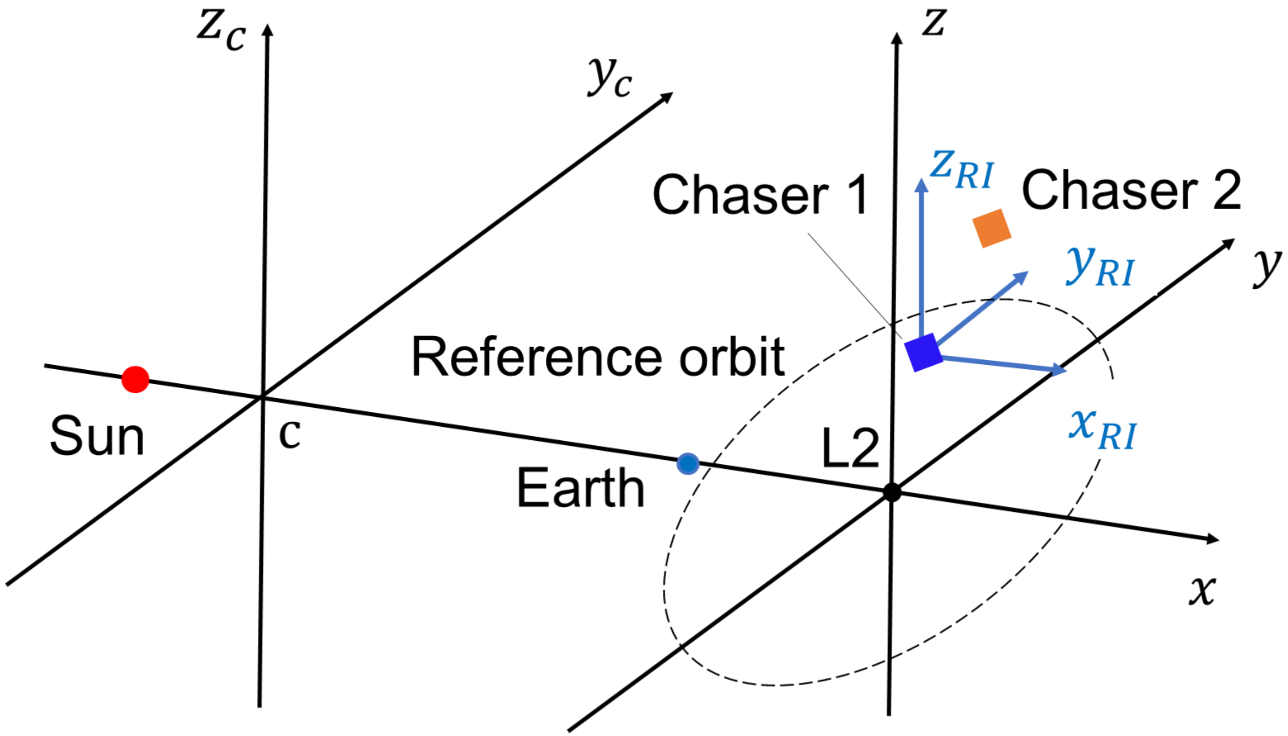
Orbit Design

◆Flowchart of fuel-free formation flight



◆ Coordinate definitions



Circular Restricted 3 Body Problem (CR3BP)

◆ Equation of motion

$$\begin{cases} \ddot{x} - 2\dot{y} = -\dfrac{\partial \overline{U}}{\partial x} + a_x \\ \ddot{y} + 2\dot{x} = -\dfrac{\partial \overline{U}}{\partial y} + a_y \\ \ddot{z} = -\dfrac{\partial \overline{U}}{\partial z} + a_z \end{cases}$$

$$\overline{U} = -\frac{1}{2}\left((x + 1 - \mu \pm \gamma)^2 + y^2\right) - \frac{1-\mu}{r_S} - \frac{\mu}{r_E}$$

◆ Orbit Design

➢ Separate design of reference and relative orbits

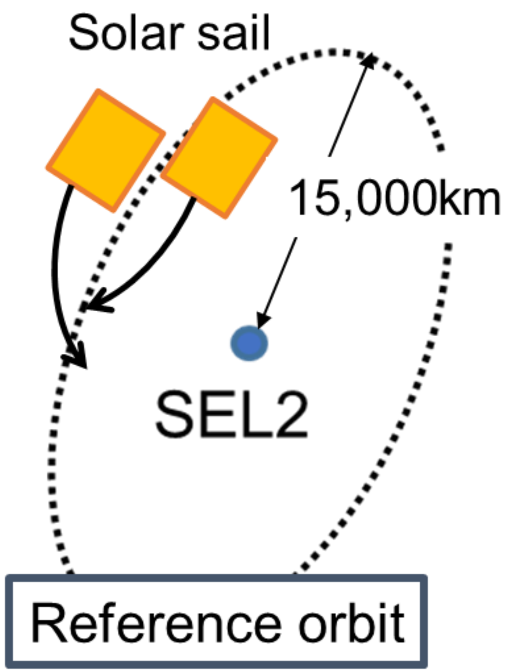
Reference orbit

● Artificial Halo orbit (Small circular Halo orbit)

Semi-major axis 15,000 [km] ← $\frac{1}{50}$ — Natural halo orbit

Advantages

- More stationary thermal condition
- Easy communication with the Earth



◆ Orbit Design

➢ Separate design of reference and relative orbits

Reference orbit

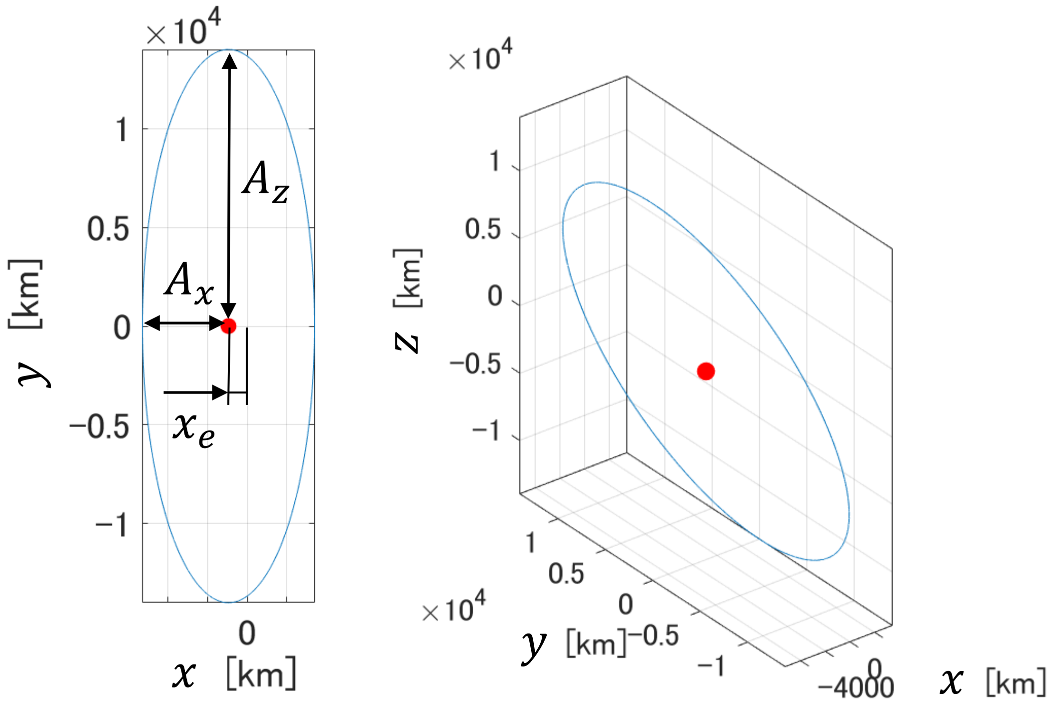
● Artificial Halo orbit (Small circular Halo orbit)

Semi-major axis 15,000 [km]

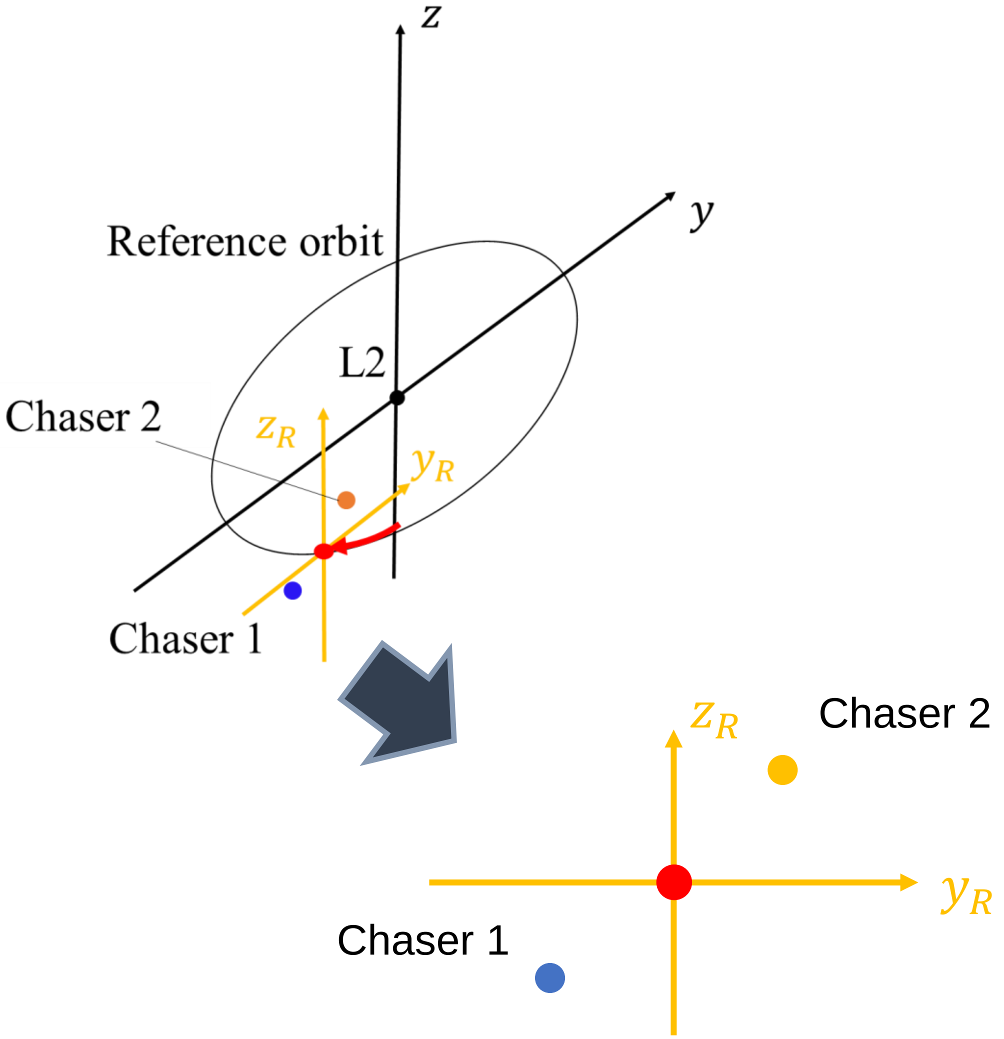
Advantages

- More stationary thermal condition
- Easy communication with the Earth

$$\begin{cases} x = -A_x \cos(\omega t) + x_e \\ y = \alpha A_x \sin(\omega t) \\ z = A_z \cos(\omega t) \end{cases}$$

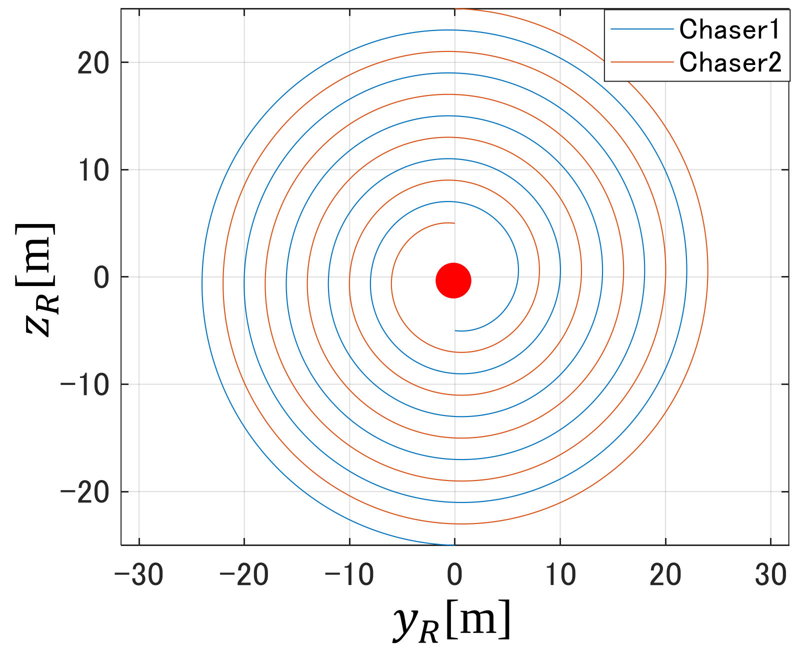


- Design relative orbit

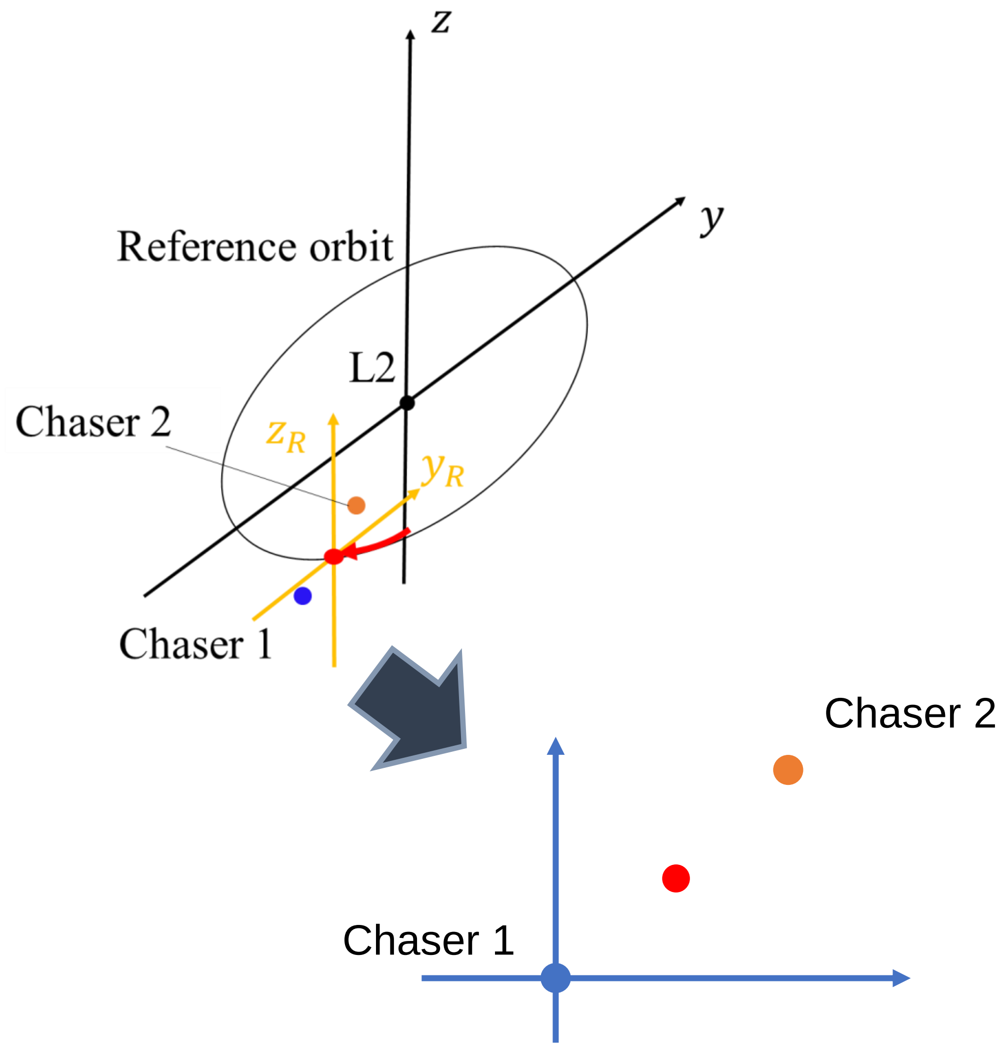


- Chaser 1 $\begin{cases} x_R = 0 \\ y_R = -(r + at)\sin(\omega_R t) \\ z_R = (r + at)\cos(\omega_R t) \end{cases}$

- Chaser 2 $\begin{cases} x_R = 0 \\ y_R = (r + at)\sin(\omega_R t) \\ z_R = -(r + at)\cos(\omega_R t) \end{cases}$



- Design relative orbit



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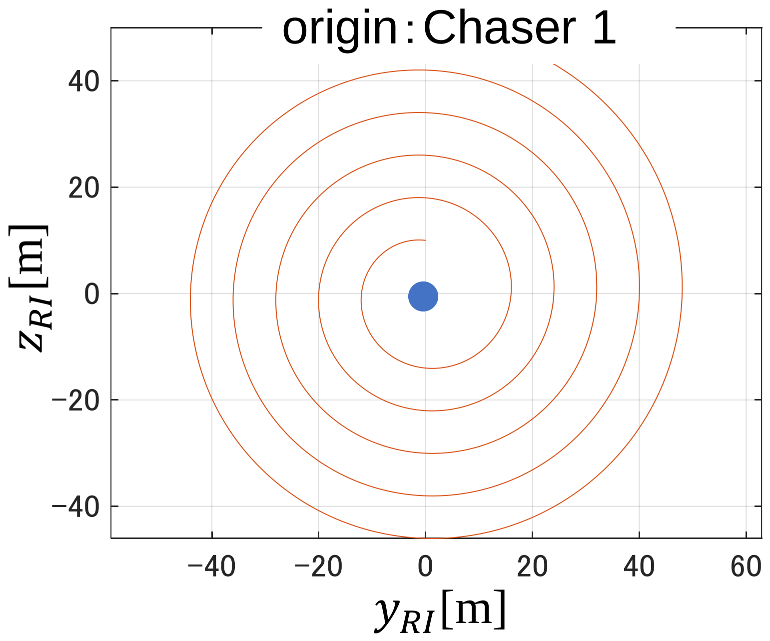
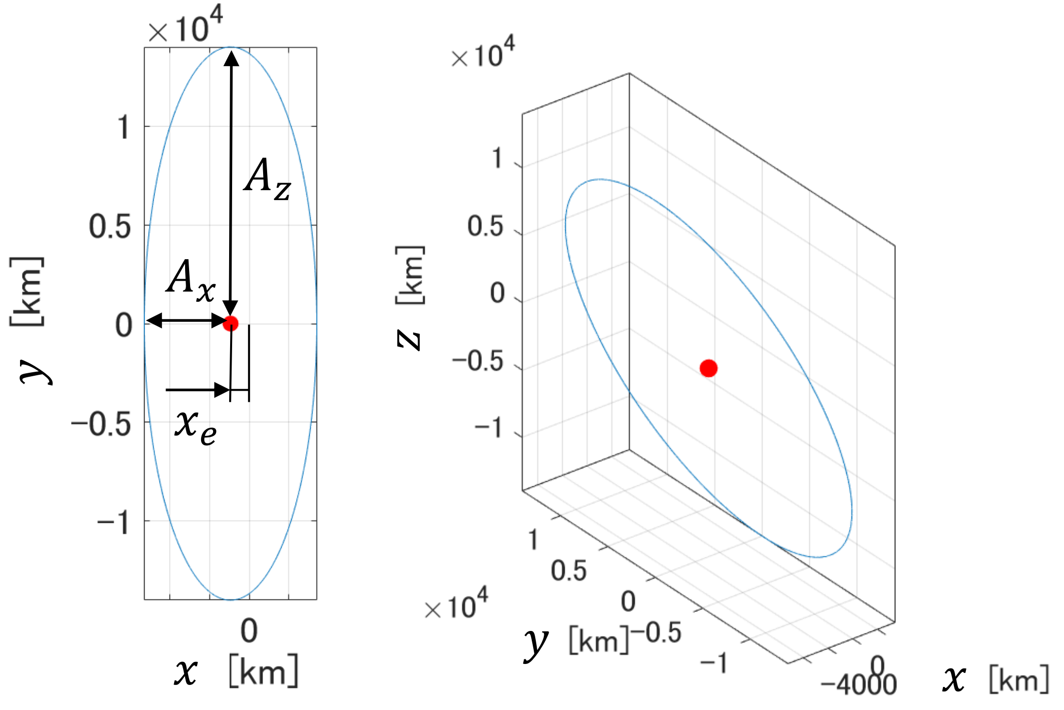


Orbit Design

- Designed by superposing a reference orbit and a relative orbit

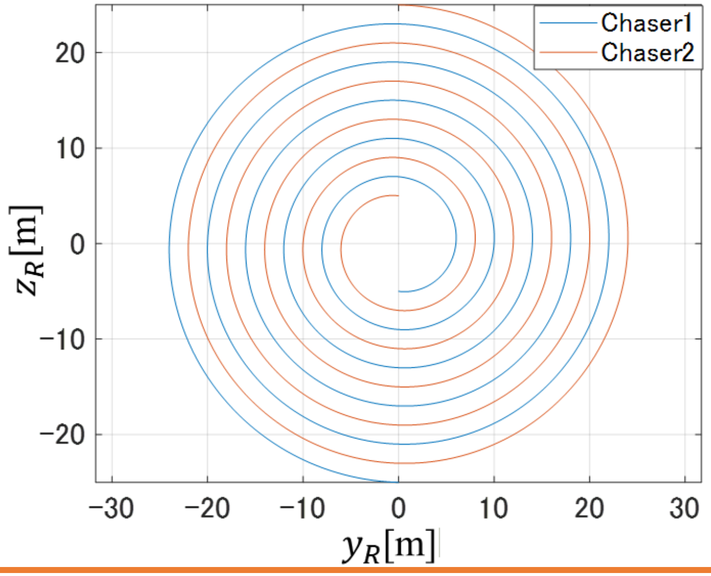
$\mathbf{x}_{\mathbf{nom}} =$

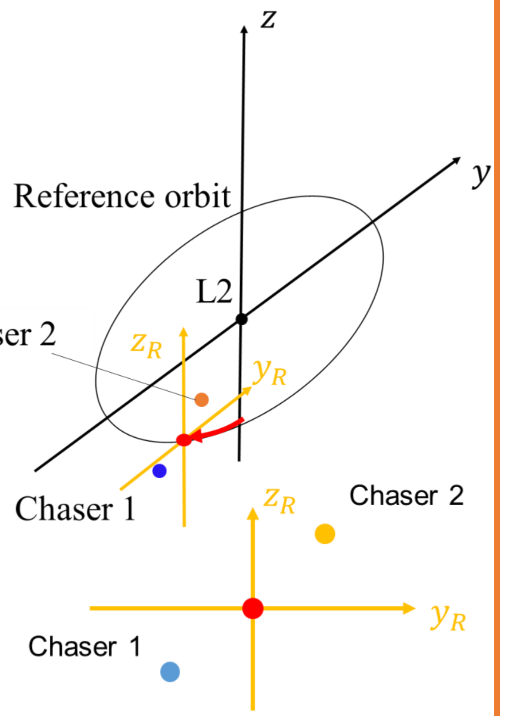
$$\begin{cases} x = -A_x \cos(\omega t) + x_e \\ y = \alpha A_x \sin(\omega t) \\ z = A_z \cos(\omega t) \end{cases}$$



+

$$\begin{cases} x_R = 0 \\ y_R = -(r + at)\sin(\omega_R t) \\ z_R = (r + at)\cos(\omega_R t) \end{cases}$$





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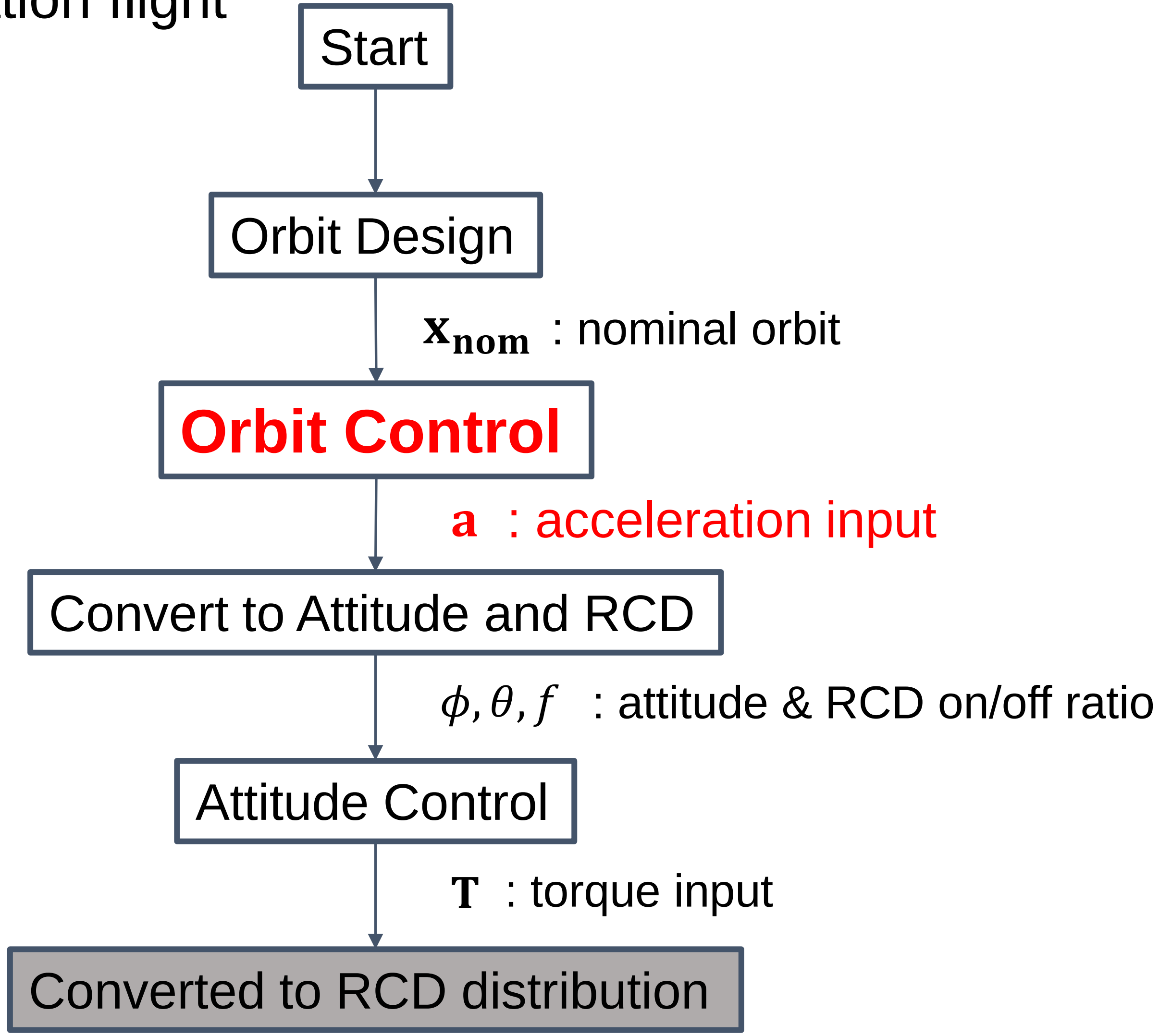
◆Flowchart of fuel-free formation flight



- Orbit control (Feed-forward control)
  - Equation of motion (CR3BP)

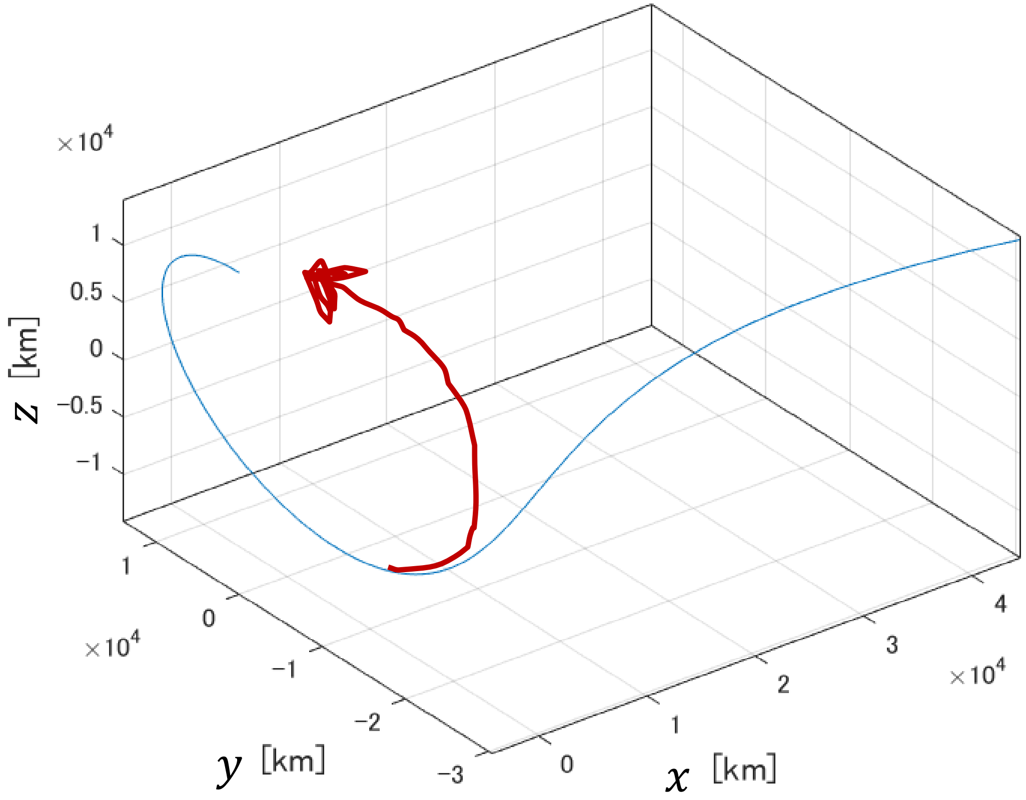
$$\begin{cases} \ddot{x} - 2\dot{y} = -\dfrac{\partial \bar{U}}{\partial x} + a_x \\ \ddot{y} + 2\dot{x} = -\dfrac{\partial \bar{U}}{\partial y} + a_y \\ \ddot{z} = -\dfrac{\partial \bar{U}}{\partial z} + a_z \end{cases}$$

x, y, z : Equation of reference orbit & relative orbit

$$\mathbf{a}_{\mathrm{ff}} = [a_x \quad a_y \quad a_z]^T$$

Feed-forward control

Feed-forward control + **Feedback control**



Control Method

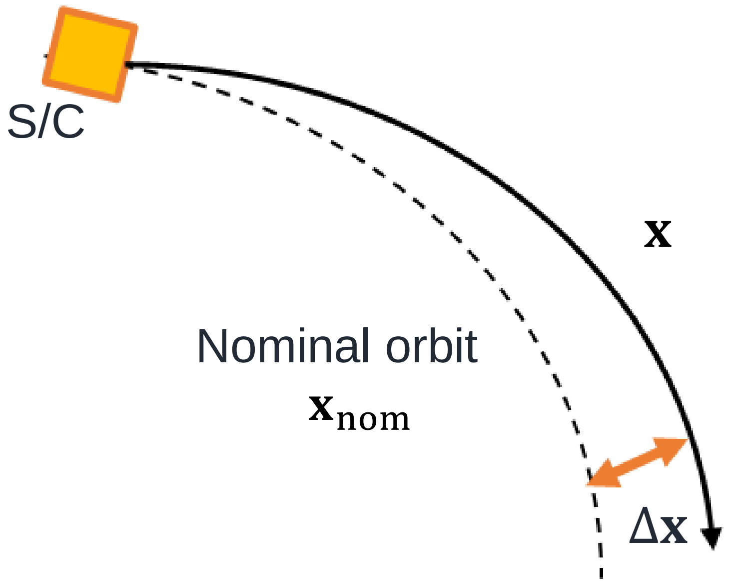
- Orbit control (Feedback control)
  - ➢ The **SDRE method** is used for control

☐ **SDRE** method (State-dependent Riccati Equation)

- **Objective function**

$$J = \int_0^{\infty} (\Delta\mathbf{x}^T \mathbf{Q}(\mathbf{x}) \Delta\mathbf{x} + \mathbf{a}_{\mathrm{fb}}{}^T \mathbf{R}(\mathbf{x}) \mathbf{a}_{\mathrm{fb}}) dt$$

→ minimize



Optimal feedback

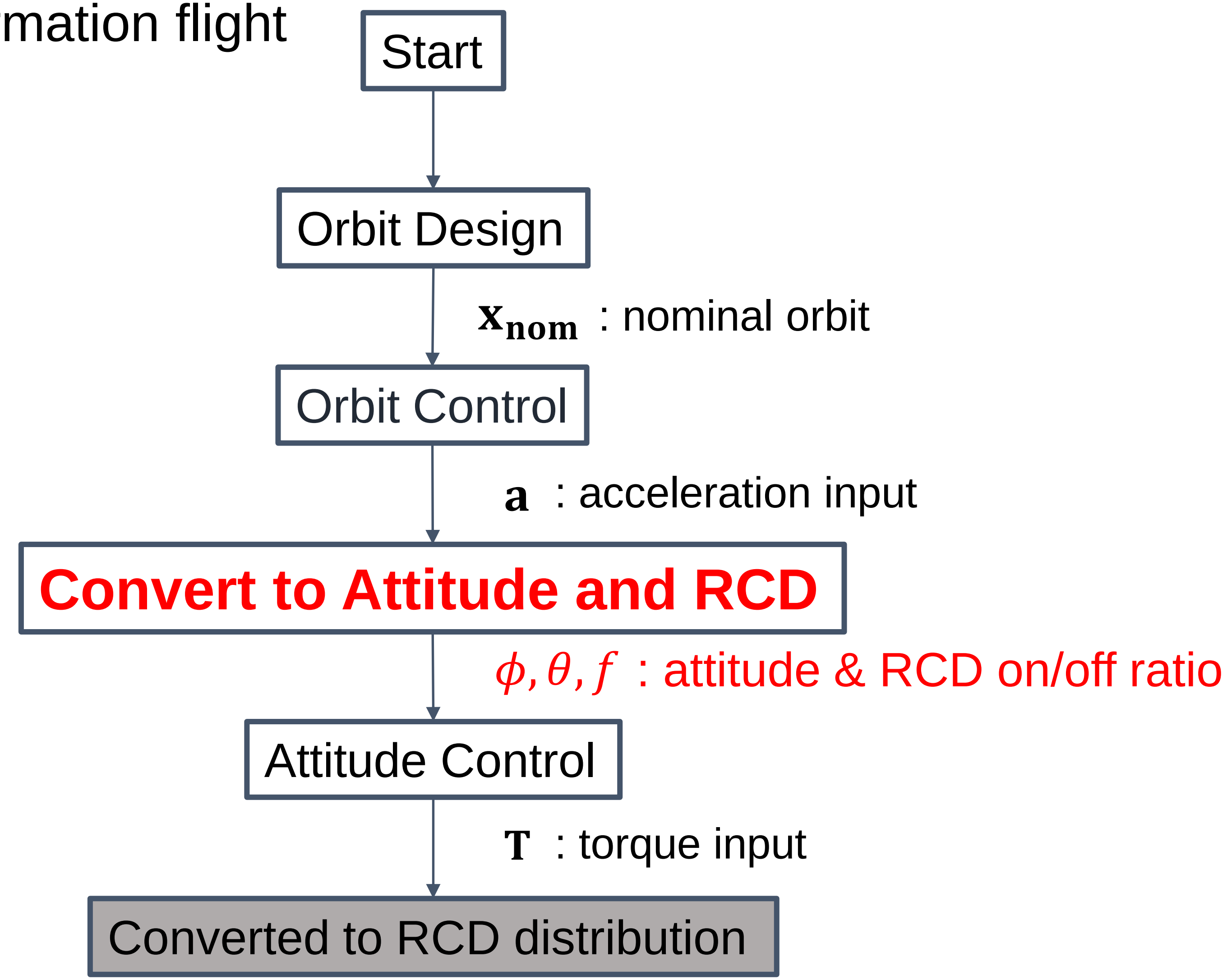
$$\mathbf{a}_{\mathrm{fb}} = -\mathbf{R}^{-1} \mathbf{B}(\mathbf{x})^T \mathbf{P}(\mathbf{x}) \Delta\mathbf{x}$$

$$\mathbf{a} = \mathbf{a}_{\mathrm{ff}} + \mathbf{a}_{\mathrm{fb}}$$

→ Conversion of control input ($\mathbf{a}$) to acceleration by SRP ($\mathbf{a}_{\mathrm{srp}}$)

Control Method

◆Flowchart of fuel-free formation flight



Control Method

◆ Express the required acceleration in terms of acceleration by SRP

$$\mathbf{a}_{\mathrm{srp}} = -\frac{PA}{m}(\mathbf{s}\cdot\mathbf{n})\Bigg[(1-f)\left\{(C_{\mathrm{absOFF}}+C_{\mathrm{difOFF}})\mathbf{s}+\left(\frac{2}{3}C_{\mathrm{difOFF}}+2(\mathbf{s}\cdot\mathbf{n})C_{\mathrm{speOFF}}\right)\mathbf{n}\right\} + f\left\{(C_{\mathrm{absON}}+C_{\mathrm{difON}})\mathbf{s}+\left(\frac{2}{3}C_{\mathrm{difON}}+2(\mathbf{s}\cdot\mathbf{n})C_{\mathrm{speON}}\right)\mathbf{n}\right\}\Bigg]$$

$$\mathbf{n} = \begin{bmatrix}\cos\phi\cos\theta\\ \cos\phi\sin\theta\\ -\sin\phi\end{bmatrix}$$

$$\mathbf{s} \sim \begin{bmatrix}-1\\ 0\\ 0\end{bmatrix}$$

$f = \frac{A_{\mathrm{ON}}}{A}$: The ON ratio

A_{ON} : RCD area (on)

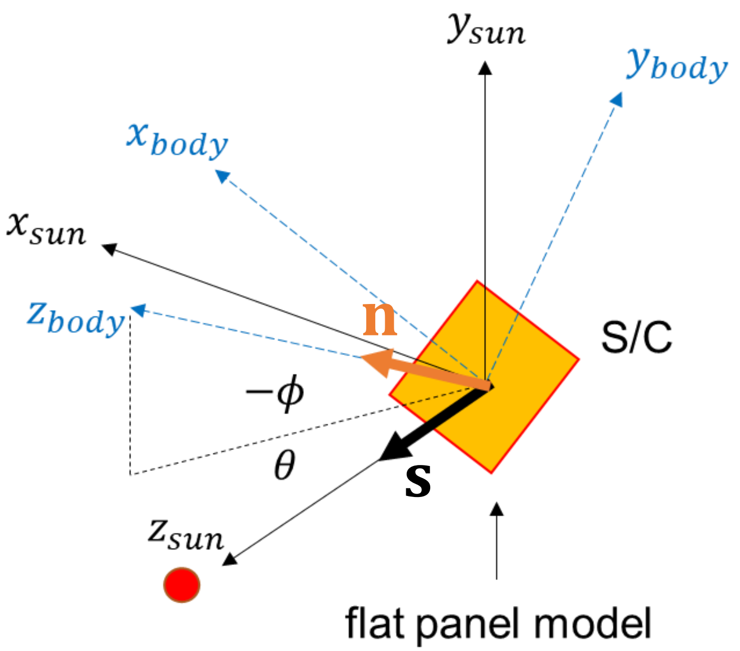
P : Ideal SRP received per 1m^2

C_{***} : Surface optical properties

A : Surface area

m : S/C mass

	C_{spe}	C_{dif}	C_{abs}
ON	0.483	0.101	0.416
OFF	0.082	0.427	0.491



□ Control input : ϕ, θ, f

Control Method

◆ Express the required acceleration in terms of acceleration by SRP

$$\mathbf{a}_{\mathrm{srp}} = -\frac{PA}{m}(\mathbf{s}\cdot\mathbf{n})\left[(1-f)\left\{(C_{\mathrm{absOFF}}+C_{\mathrm{difOFF}})\mathbf{s}+\left(\frac{2}{3}C_{\mathrm{difOFF}}+2(\mathbf{s}\cdot\mathbf{n})C_{\mathrm{speOFF}}\right)\mathbf{n}\right\} + f\left\{(C_{\mathrm{absON}}+C_{\mathrm{difON}})\mathbf{s}+\left(\frac{2}{3}C_{\mathrm{difON}}+2(\mathbf{s}\cdot\mathbf{n})C_{\mathrm{speON}}\right)\mathbf{n}\right\}\right]$$

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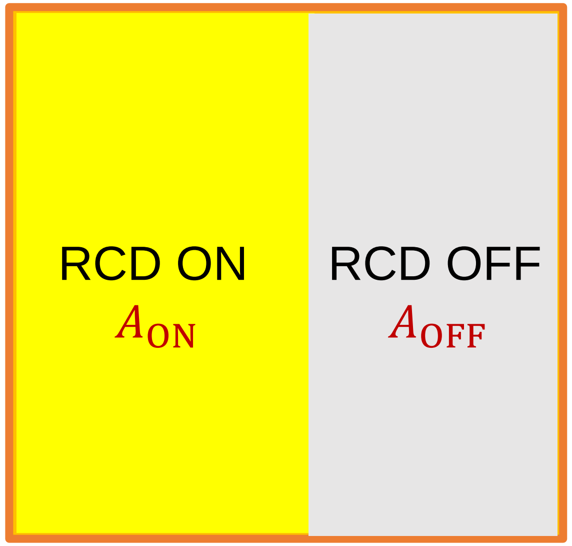

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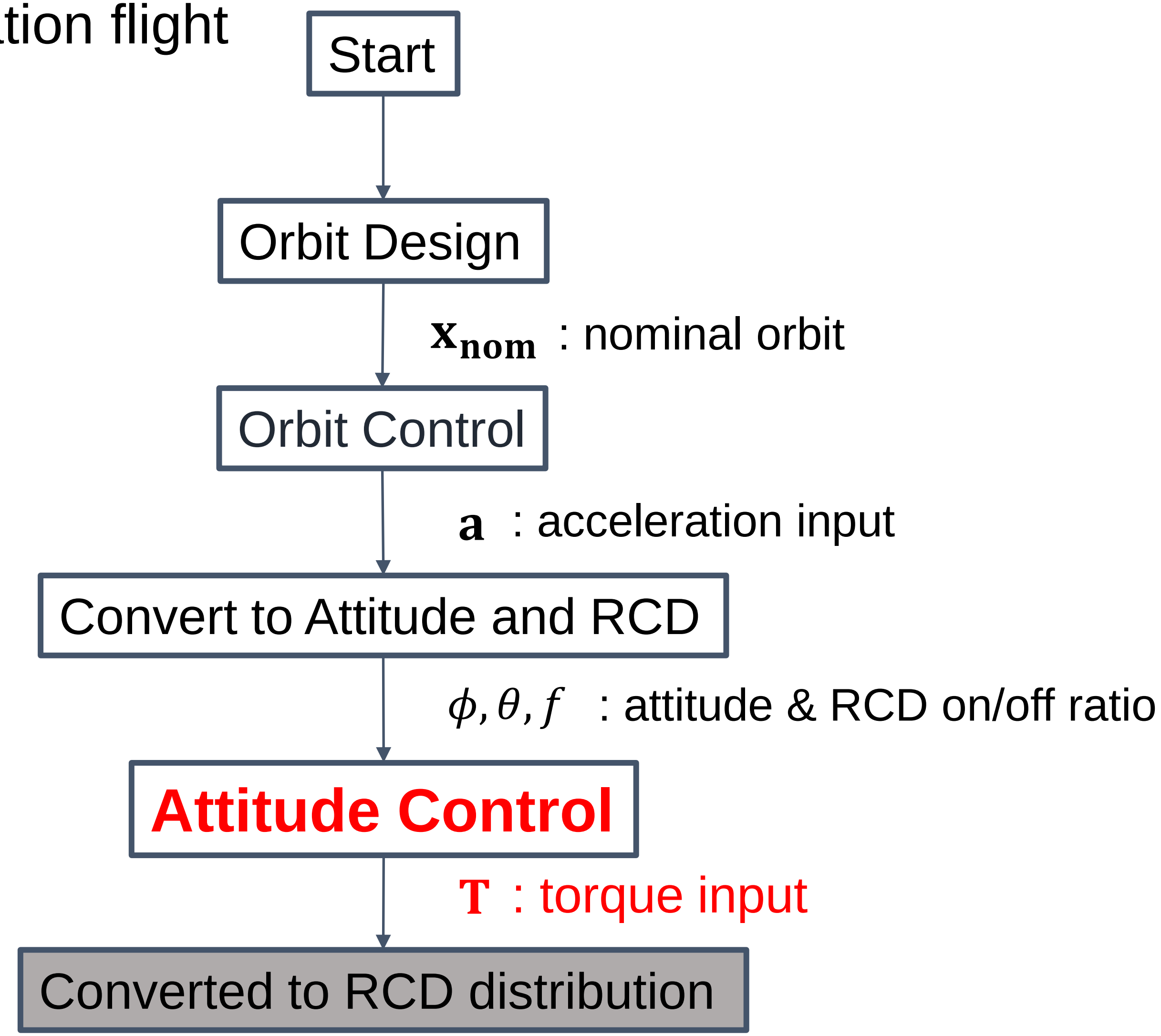
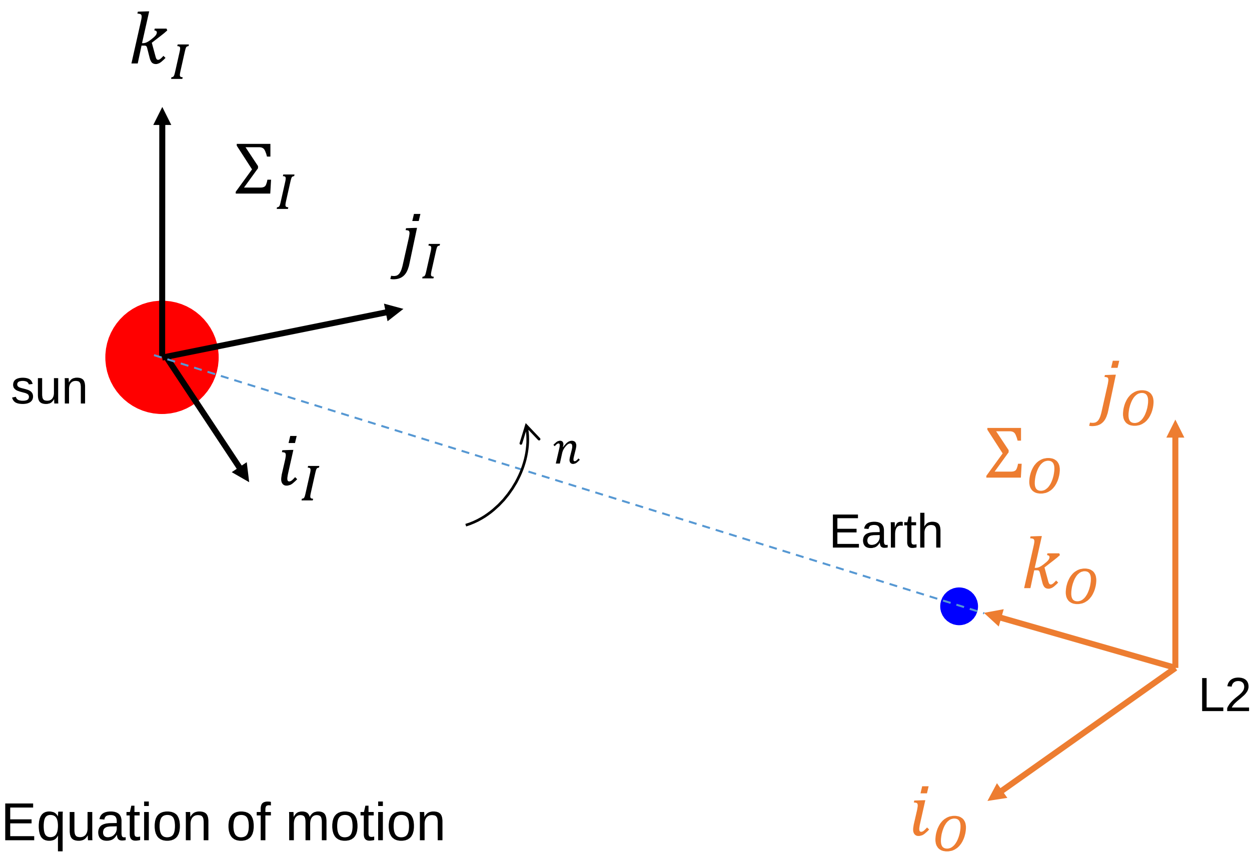
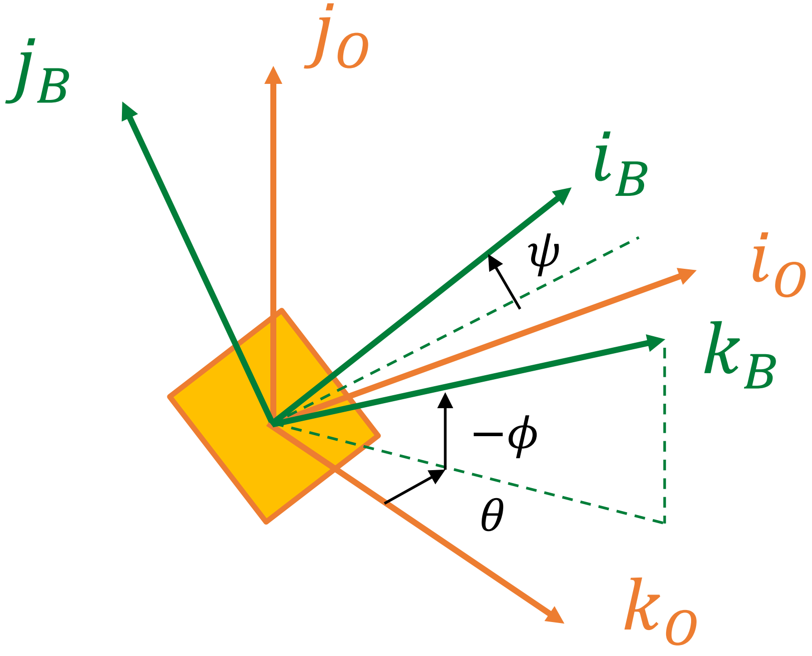


Control Method

◆ Coordinate definitions





◆ Equation of motion

$$\dot{\boldsymbol{H}} + \boldsymbol{\omega} \times \boldsymbol{H} = \boldsymbol{T}$$

$$\boldsymbol{H} = \begin{pmatrix} I_x \omega_x^I \\ I_y \omega_y^I \\ I_z \omega_z^I \end{pmatrix} \qquad \boldsymbol{\omega} = \begin{pmatrix} \omega_x^I \\ \omega_y^I \\ \omega_z^I \end{pmatrix}$$

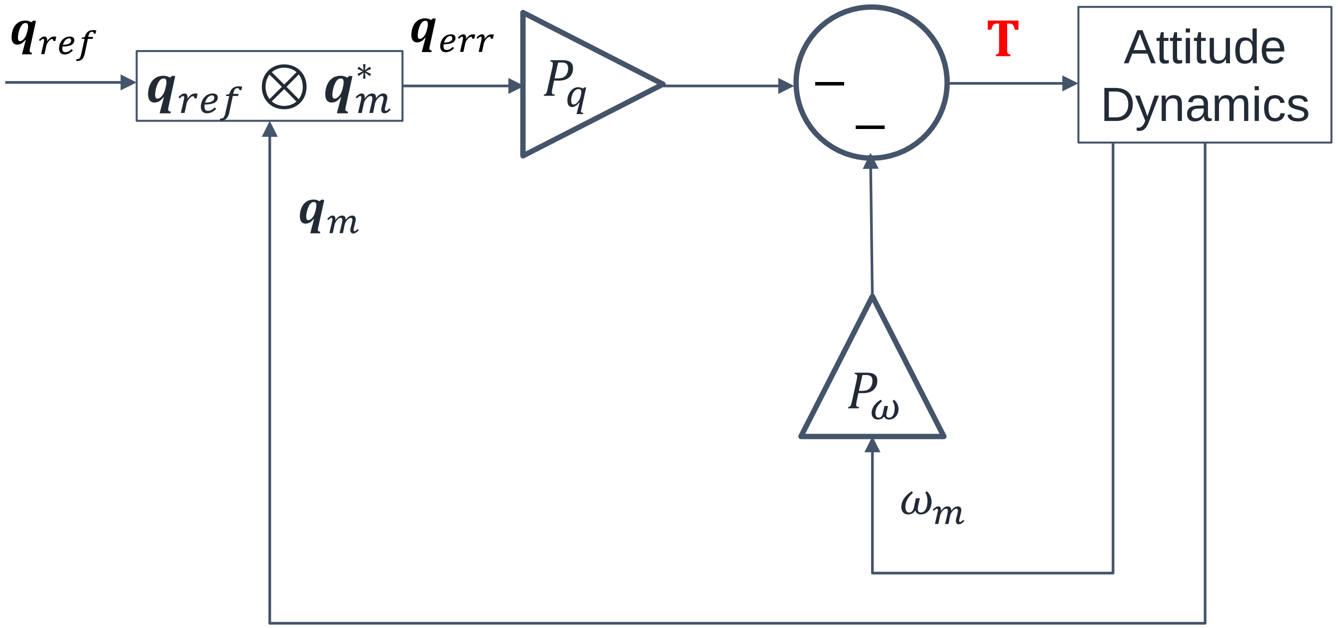
$$\dot{\boldsymbol{q}} = \frac{1}{2} \begin{bmatrix} 0 & \omega_z & -\omega_y & \omega_x \\ -\omega_z & 0 & \omega_x & \omega_y \\ \omega_y & -\omega_x & 0 & \omega_z \\ -\omega_x & -\omega_y & -\omega_z & 0 \end{bmatrix} \boldsymbol{q}$$

Control Method

- Attitude control
  - The P^2 control (nonlinear full quaternion control) is used for control

□ P^2 control : Control to reference attitude and angular velocity

- Toughness to large angles due to full quaternion
- Non-linear control



$\boldsymbol{q}_{ref}$	: reference attitude (quaternion)
q_m	: current attitude (quaternion)
q_{err}	: error attitude (quaternion)
$\mathbf{T}$	: control torque
ω_m	: current angular velocity
P_q, P_ω	: gain

Control Method

◆ Feedback control cycle

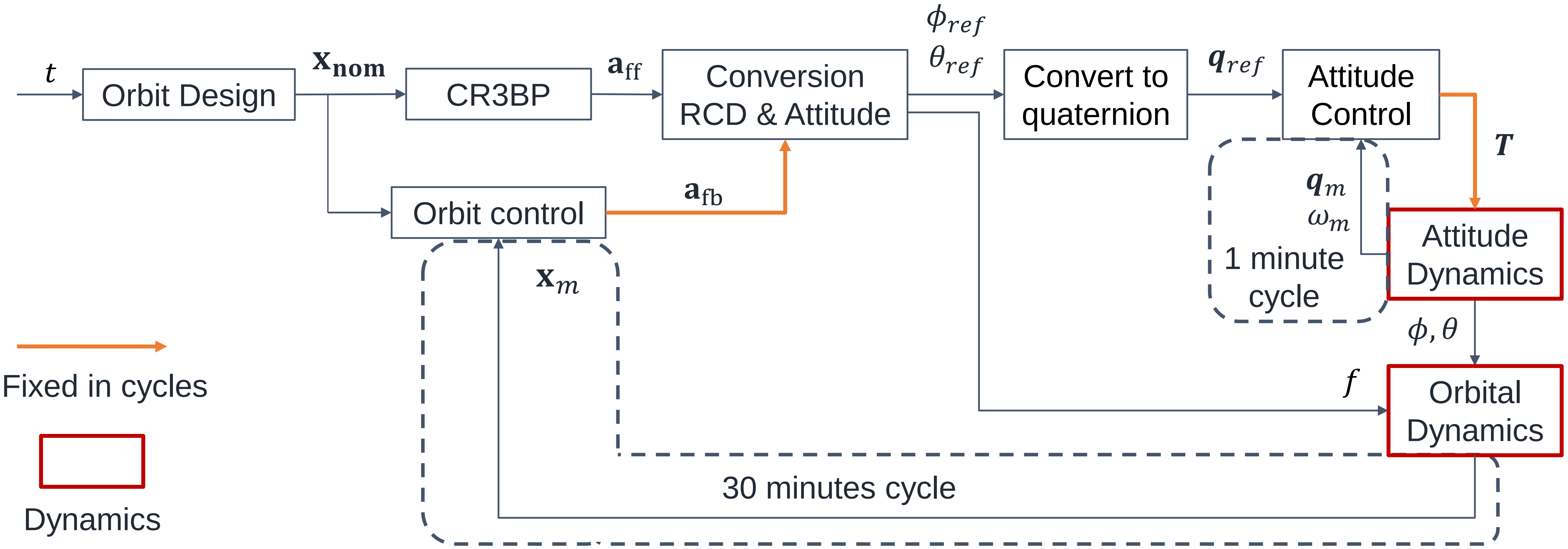
- Orbit control : 30 minutes
- Attitude control : 1 minute

$\mathbf{x}_{\mathbf{nom}}$: nominal orbit

$\mathbf{a}$: acceleration input

$\mathbf{T}$: torque input

f : ON ratio



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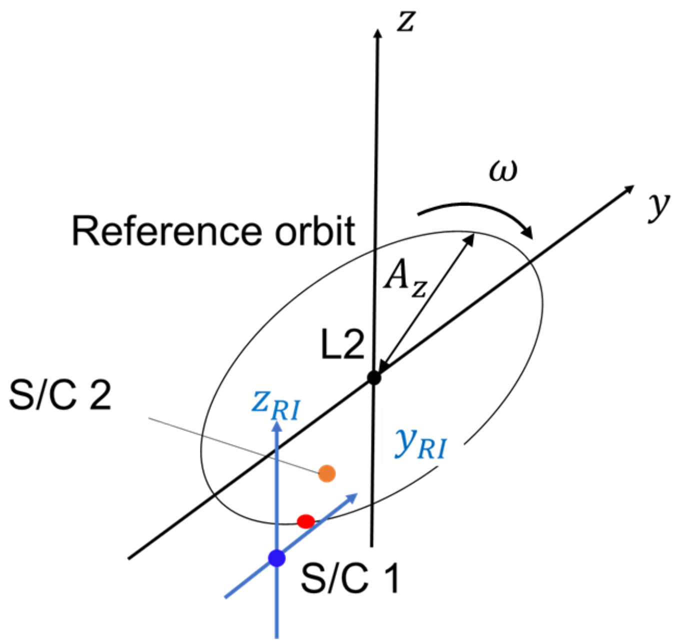
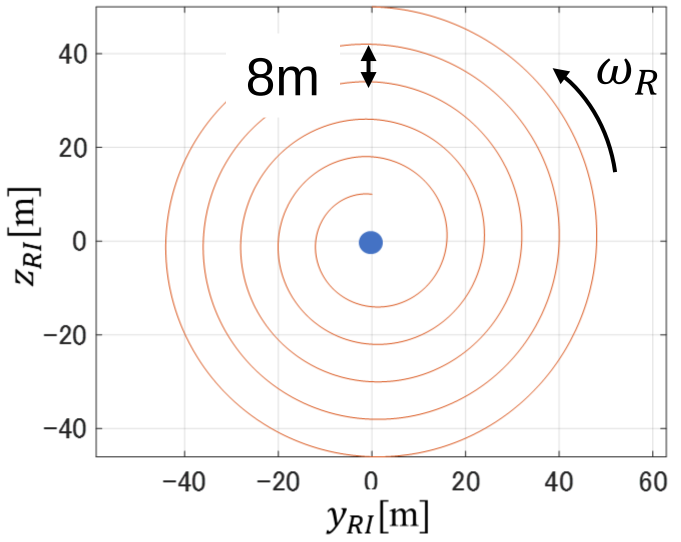




◆ Orbital properties

Small halo orbit angular velocity ω [deg/day]	1.9895
Semi-major axis A_z [km]	14,000
Initial position r_R [m]	5
Relative orbital angular velocity ω_R [deg/day]	79.58
Equilibrium point movement x_e [km]	-1194.9
Area divided by mass A/M [km²/kg]	6.67×10^{-8}

A/M (IKAROS) : 6.5×10^{-7} km²/kg

◆ Attitude properties

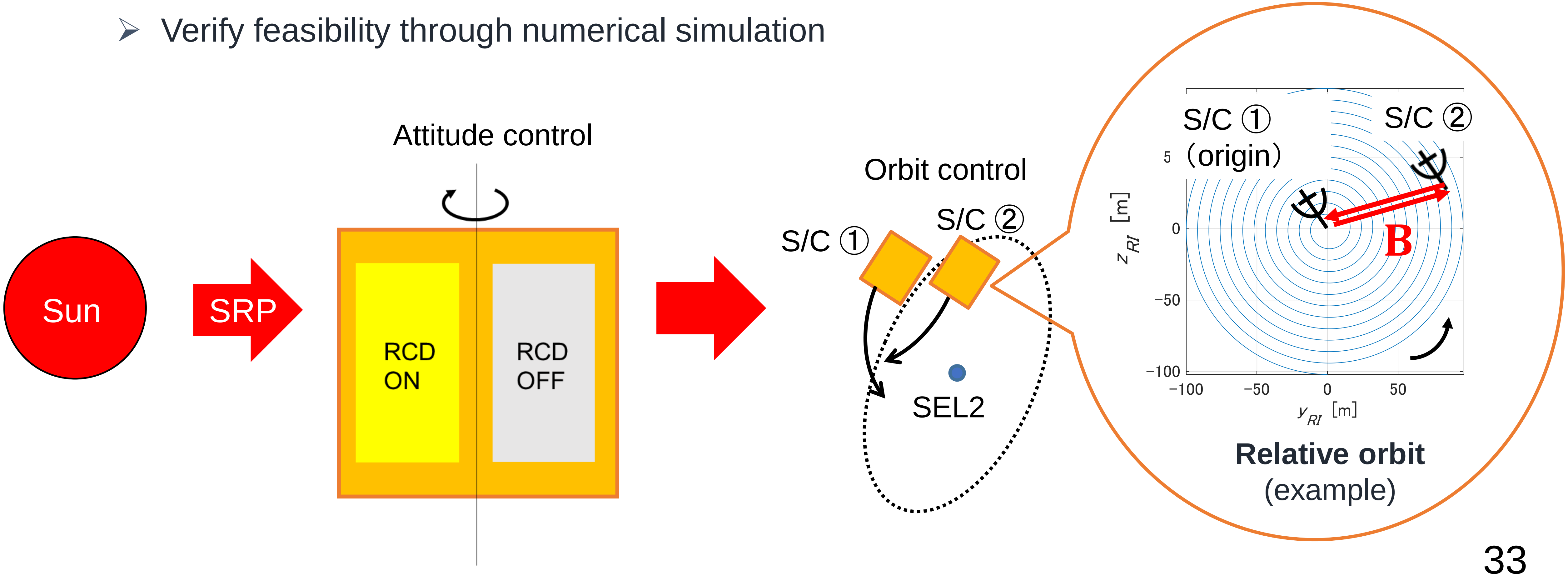
Chaser 1 initial angle (ϕ, θ, ψ) [deg]	$(-13.73 \quad 0 \quad 0)$
Chaser 1 initial angle (ϕ, θ, ψ) [deg]	$(-14.00 \quad 0 \quad 0)$
Initial angular velocity $(\dot{\phi}, \dot{\theta}, \dot{\psi})$ [deg/s]	$(0 \quad 0 \quad 0)$
$\boldsymbol{I} = (I_{xx} \quad I_{yy} \quad I_{zz})^T$ [kg^2/m^2]	$(400 \quad 400 \quad 780)^T$

Propagation time：181 days (Reference orbit 1 revolutions)

Purpose of this research

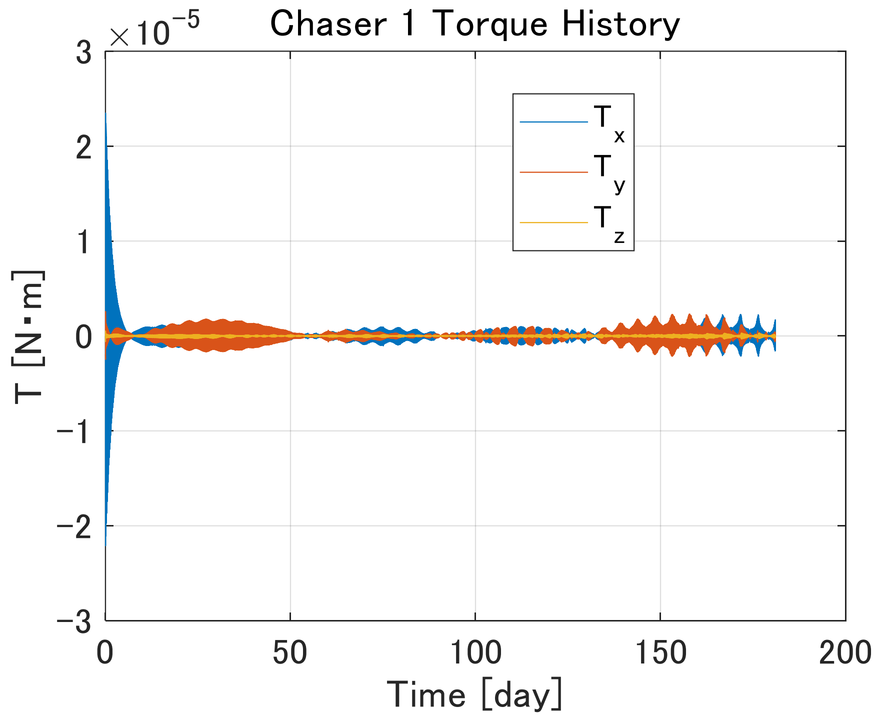
Completely **fuel-free formation flight interferometric observations** by simultaneous **orbit and attitude control** of solar sails using RCD

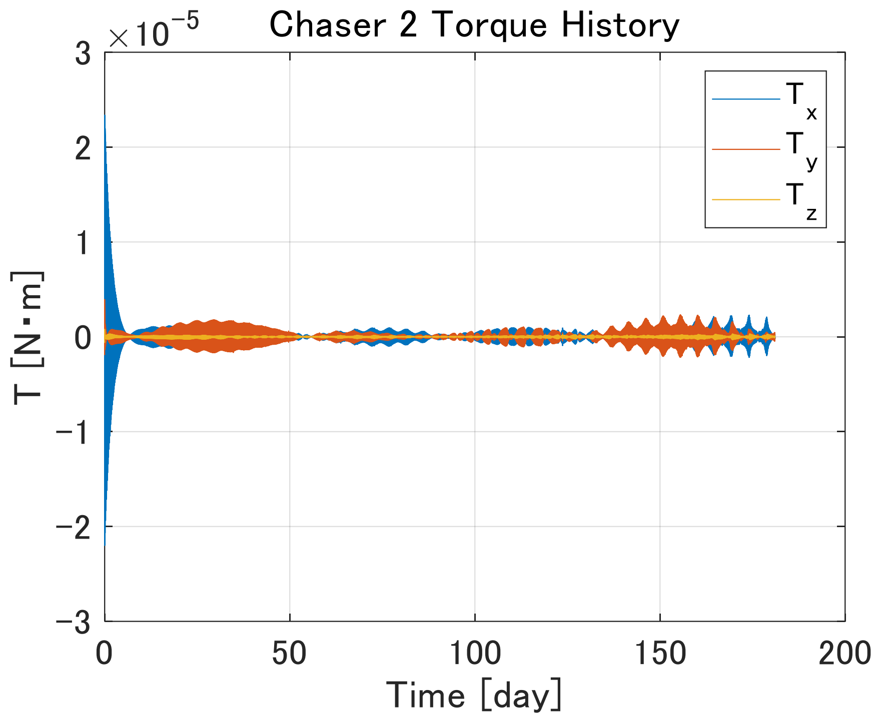
- Verify feasibility through numerical simulation



◆ Torque history

The initial attitude angular velocity is 0, so the initial torque applied is considered to be large



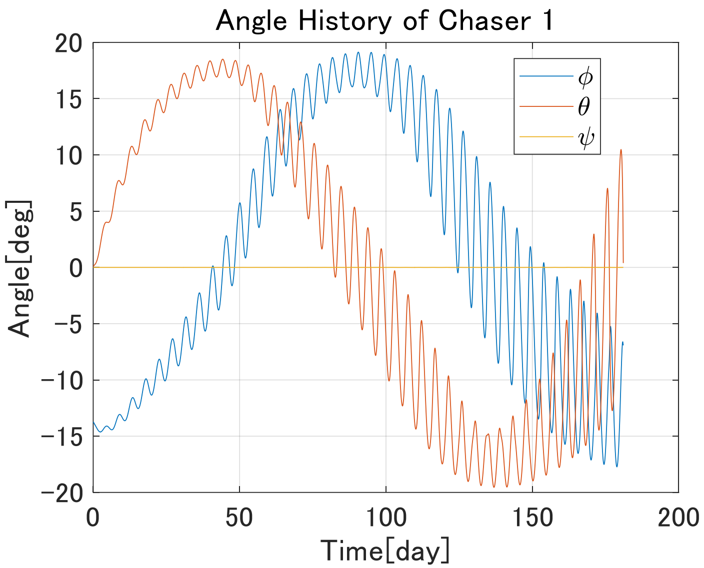


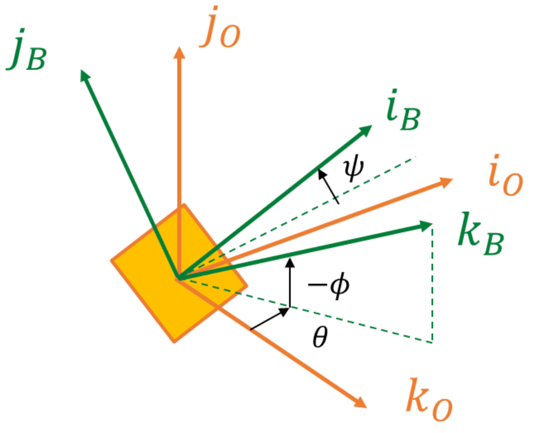
This torque is of the order of what can be achieved by SRP

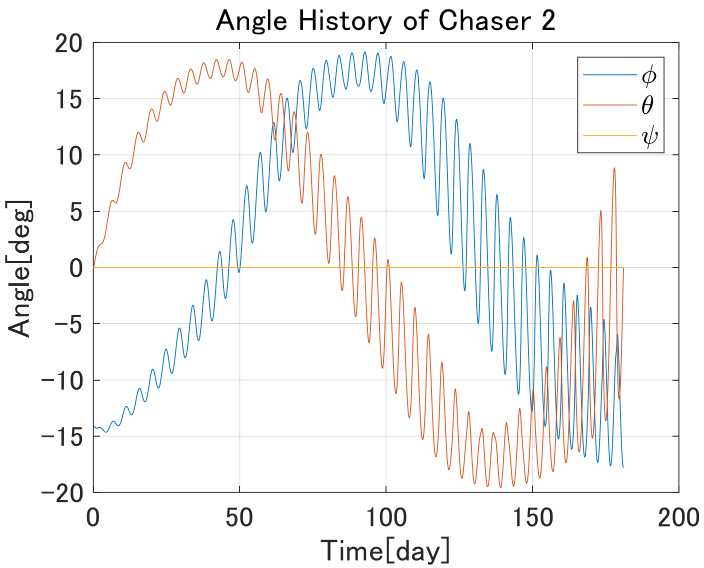
Simulation

Result : control input

Angle history

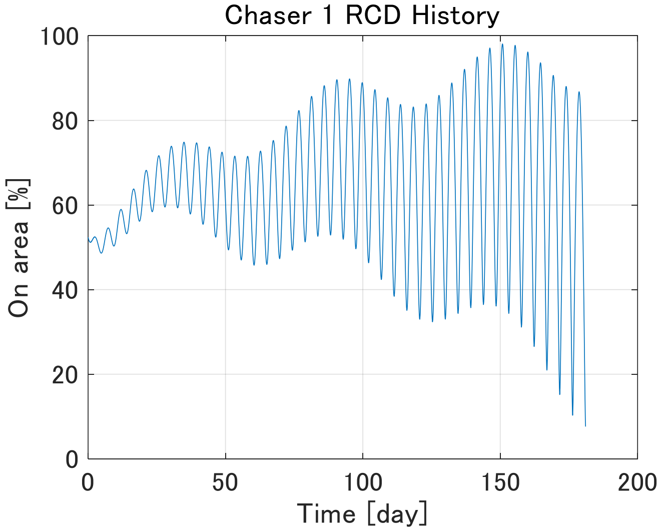


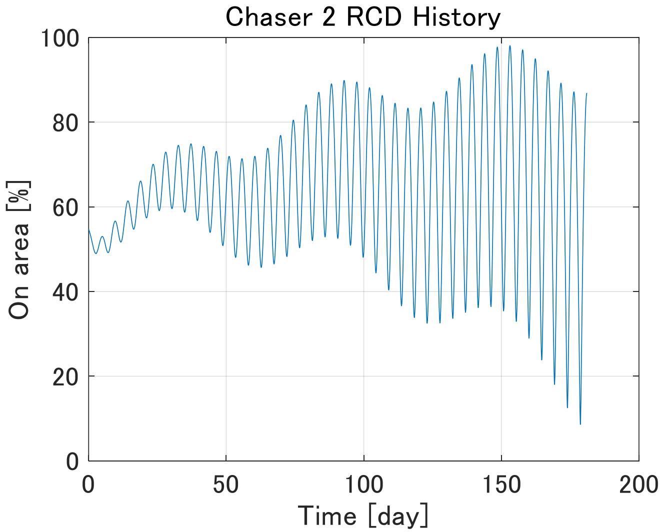




- Chaser 1
- Chaser 2

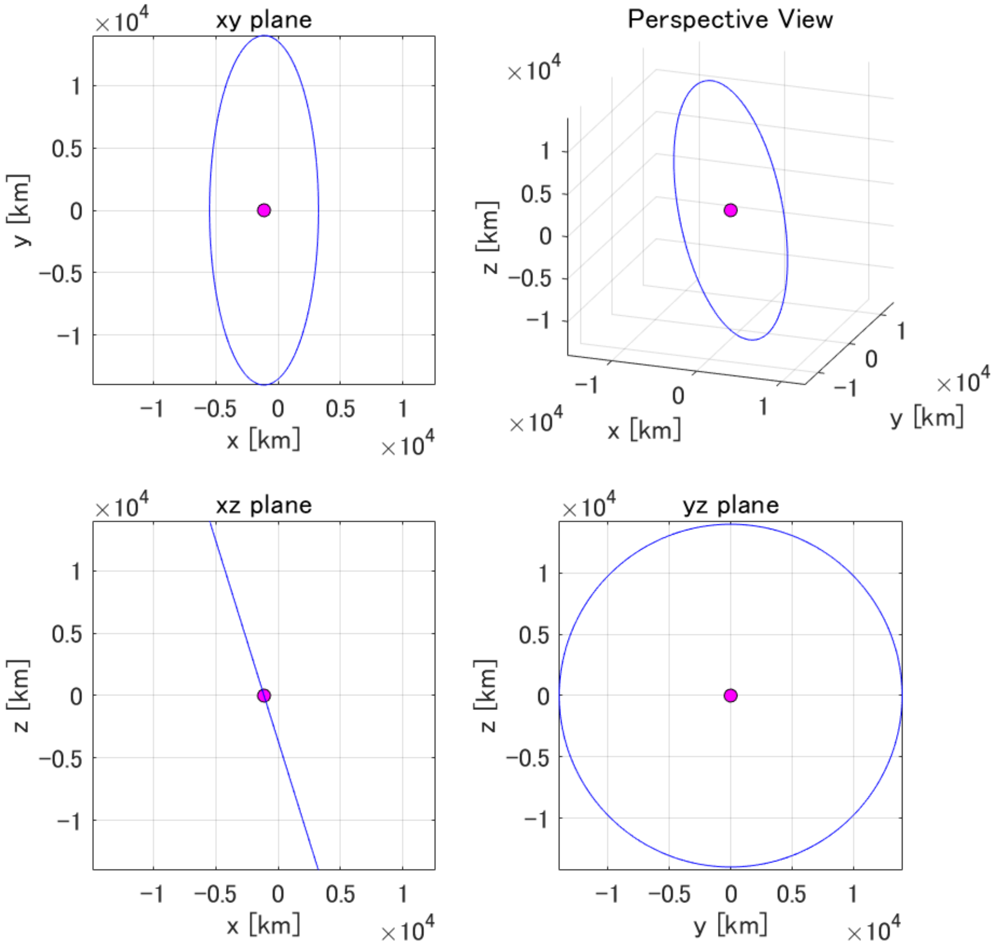
RCD ON ratio history

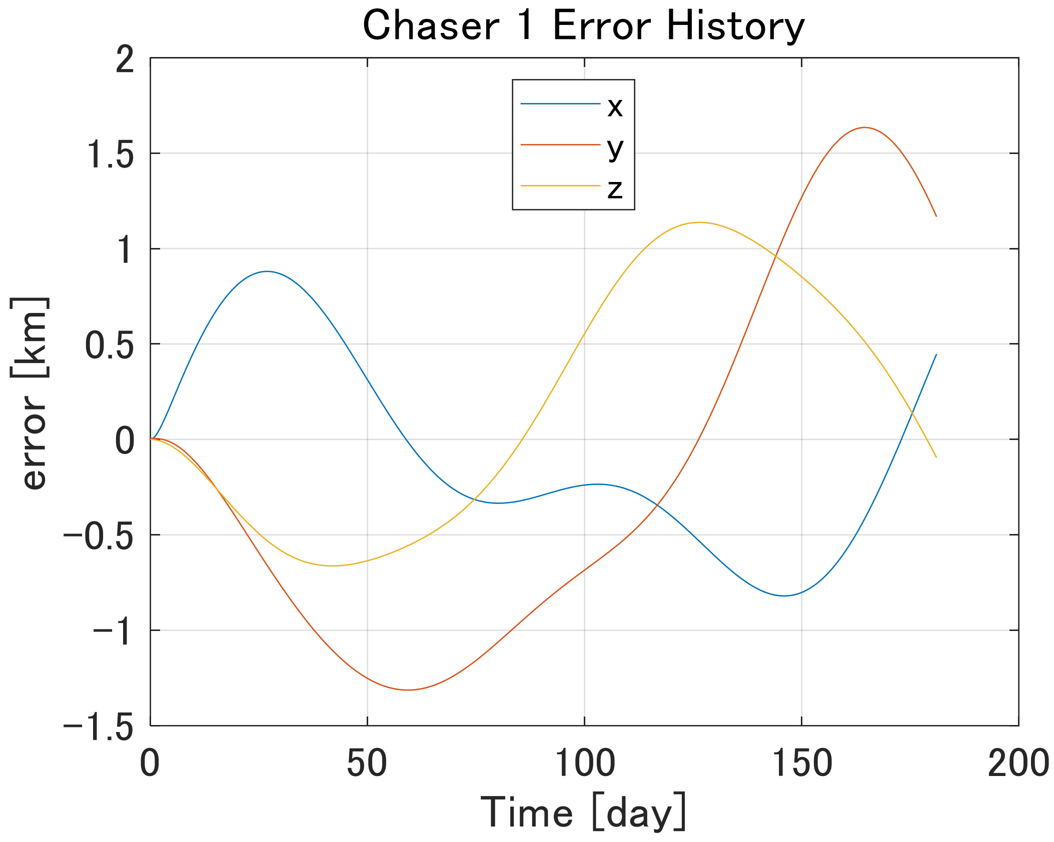




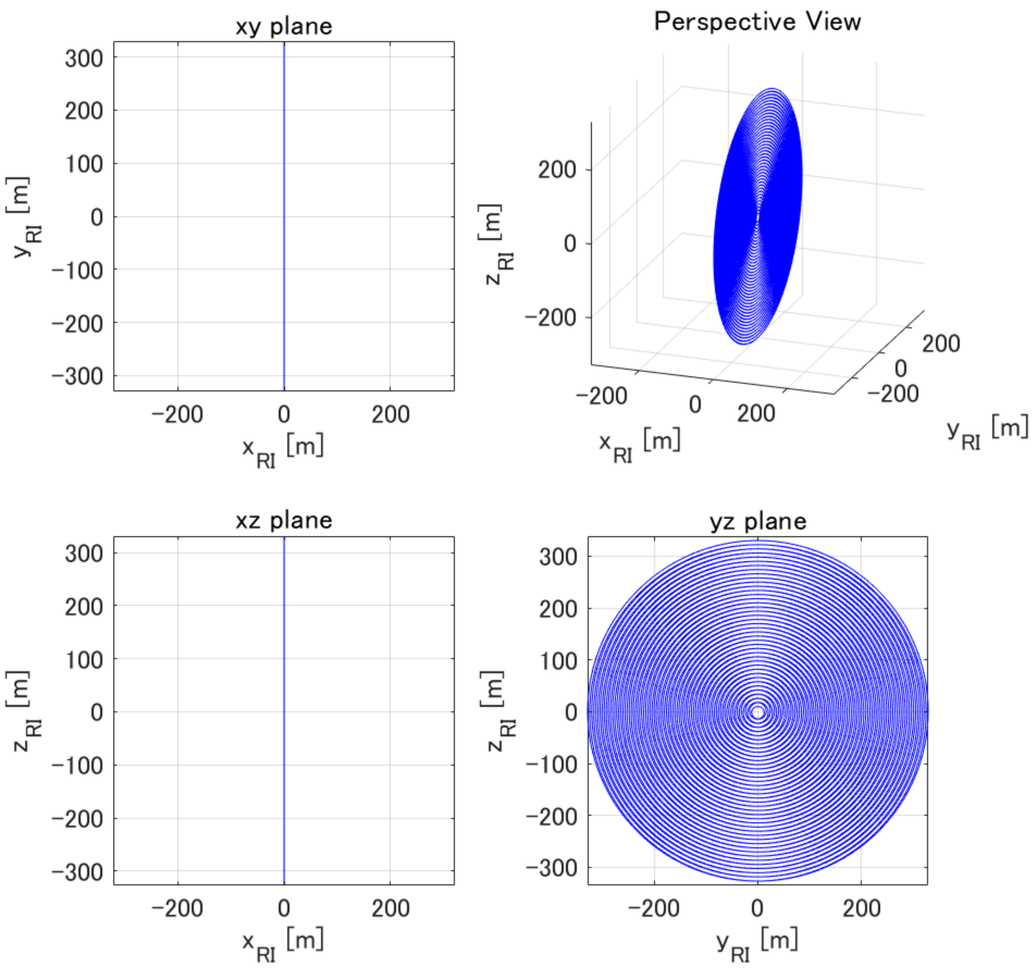
The reference orbit was maintained

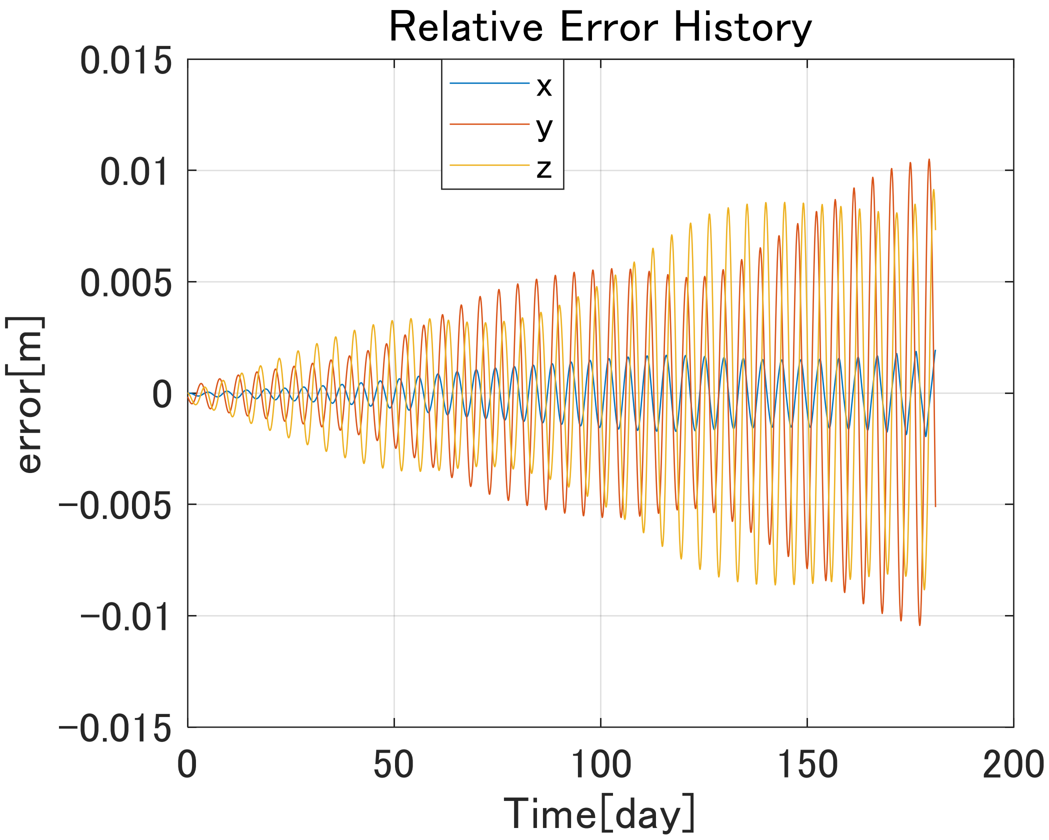
- Chaser 1





The relative orbits were also formed as designed





Contents

Summary

- Designed a relative orbit and a reference orbit, an artificial halo orbit, suitable for interferometric observations
- The SDRE method was used for orbit control
- The P^2 control was used for attitude control
- It was confirmed that orbit can be controlled by torque application

Future Work

- Create an RCD ON/OFF distribution algorithm to produce the torque derived in the present study

Attitude Control

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Converted to RCD distribution