6th International Symposium on Space Sailing

Constellation Around Small Bodies Using Spinning Solar Sails Under Simultaneous Orbit-Attitude-Structure Control

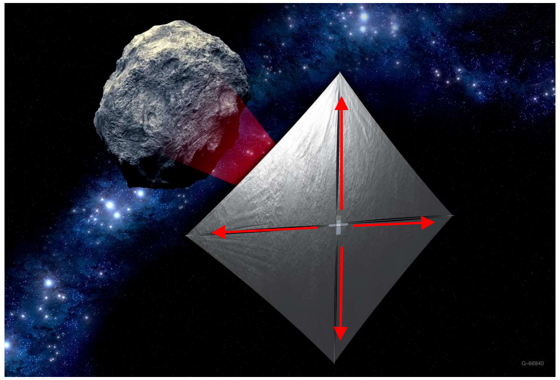
Yuki Takao[1], Osamu Mori[2], Shota Kikuchi[3], Yusuke Oki[2],
Ahmed Kiyoshi Sugihara[2], Tetsuya Kusumoto[4]

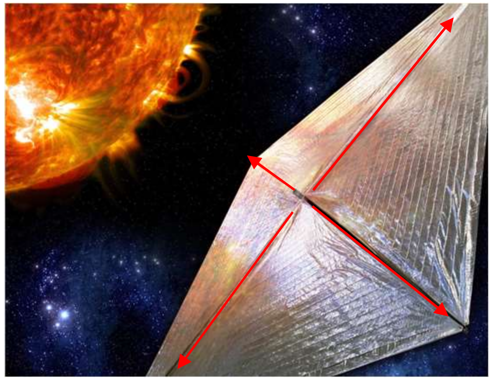
1: Kyushu University
2: Japan Aerospace Exploration Agency
3: National Astronomical Observatory of Japan
4: The University of Tokyo

Background
Two classifications of solar sails

Boom (mast) deployment

NEA Scout (NASA)



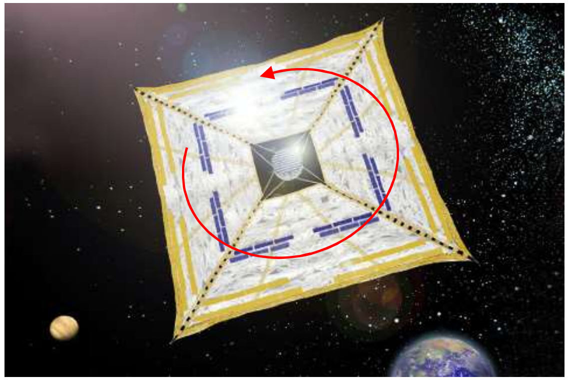


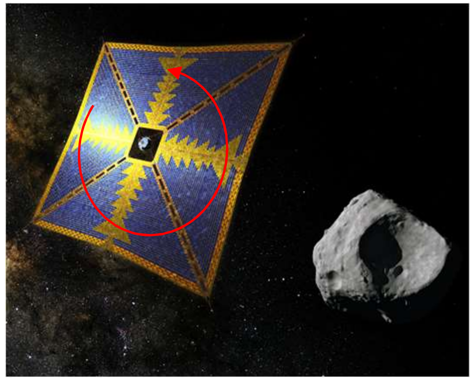
Solar Cruiser (NASA)

- Many solar sails all over the world use this method.
  - Pros: Simple storage/deployment mechanism.
  - Cons: Long, and hence heavy booms are needed for large solar sails.

Centrifugal (spin) deployment

IKAROS (JAXA)





OKEANOS (JAXA)

- Japanese original method based on Origami folding.
  - Pros: Large solar sails can be deployed without additional (supporting) structure.
  - Cons: Complex behavior of deployment.

An issue common to both methods is that <u>the sail membrane is confined within a flat surface</u>.

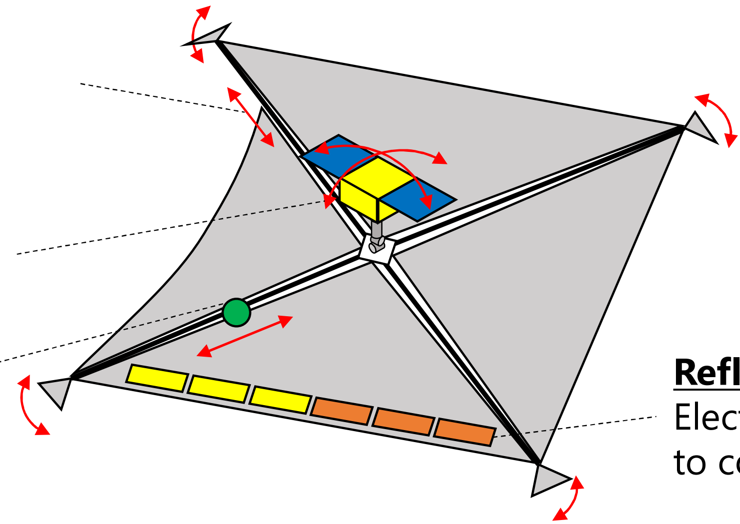
Background
Steering methods for solar sails

- A solar sail is subject to extremely large SRP disturbance as compared to other types of spacecraft.
  - Conventional attitude control using reaction wheels or thrusters is difficult in solar sails.
  - Attitude control of solar sails is often performed by manipulating the offset between the center of mass (c.m.) and center of pressure (c.p.).

Billowed wing
Billow some of the wings along the booms to change the c.p.

Gimballed mass
Swing the spacecraft main body to move the c.m.

Moving mass
Move a small mass along the boom to change the c.m.



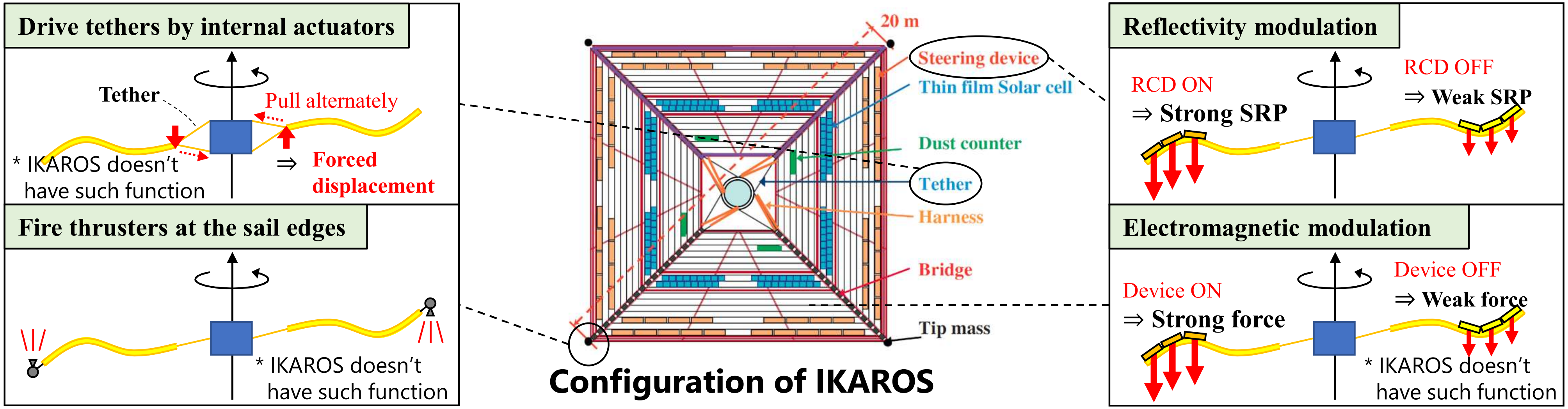
Control vane
Move vanes to control the c.p., in a similar manner as rudder and aileron of aircraft.

Reflectivity modulation
Electrically change the reflectivity to control the c.p.

What about spinning solar sails?

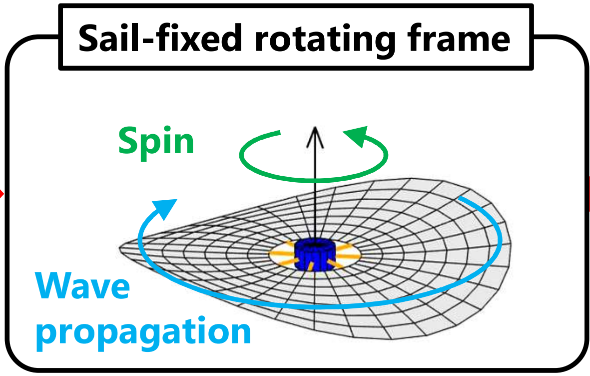
Active Shape Control of Spinning Solar Sails

We have proposed a new shape control method in which spinning solar sails are mechanically excited.

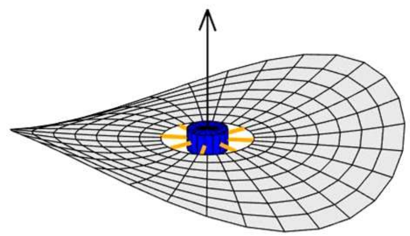


Configuration of IKAROS

Excite the spinning sail via some input



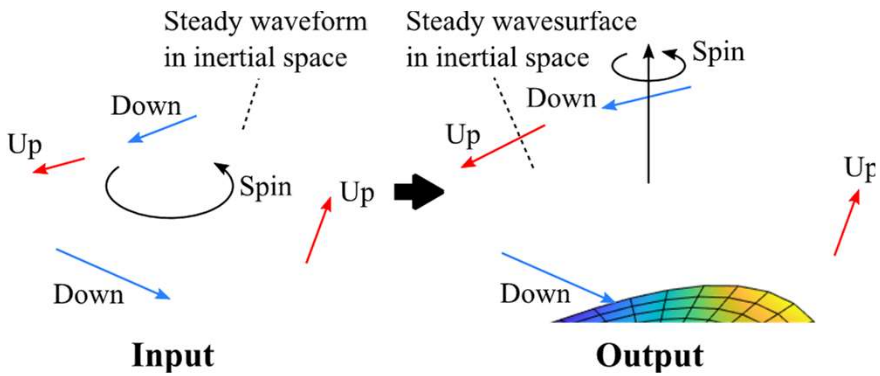
Inertial frame



Spin and wave propagation cancel each other, resulting in a steady wave surface in the inertial frame, which is called a static wave.

Mechanism of a static wave

- Qualitative understanding
  - Actuators are controlled so that the input waveform is steady in the inertial space.
  - The steady waveform is amplified by an amount depending on the frequency response, resulting in a steady wave surface in the inertial frame.



- Quantitative understanding
  - The input waveform can be written as
$$w_0(r_a, \theta, t) = A_0 \cos(m_0\theta + \omega_0 t + \alpha_0) + B_0 \cos(m_0\theta - \omega_0 t + \beta_0)$$
  - The resulting deformation is
$$w(r, \theta, t) = G(r; m_0, \omega_0) w_0$$
$$= \underline{G(r; m_0, \omega_0) A_0 \cos(m_0\theta + \omega_0 t + \alpha_0)} + \underline{G(r; m_0, \omega_0) B_0 \cos(m_0\theta - \omega_0 t + \beta_0)}$$

Wave propagating in the opposite direction to spin

Necessary condition:
The wave and spin cancel each other.
→ Wave propagation speed = $\omega_0 / m_0 = \Omega$

Wave propagating in the same direction as spin

Necessary condition:
The wave propagating in the spin direction shouldn't exist. → $B_0 = 0$

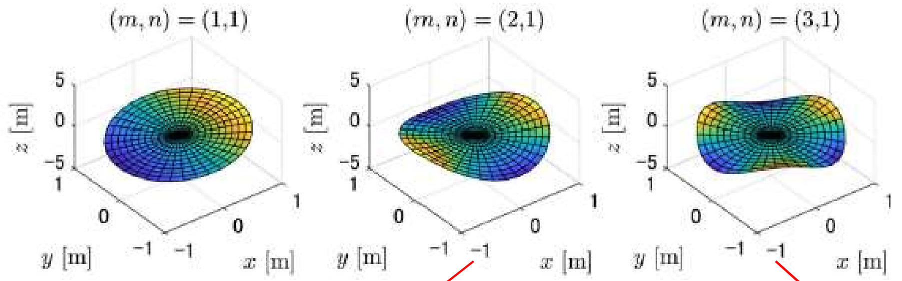
Necessary input: $w_0(r_a, \theta, t) = A_0 \cos\{m_0(\theta + \Omega t) + \alpha_0\}$

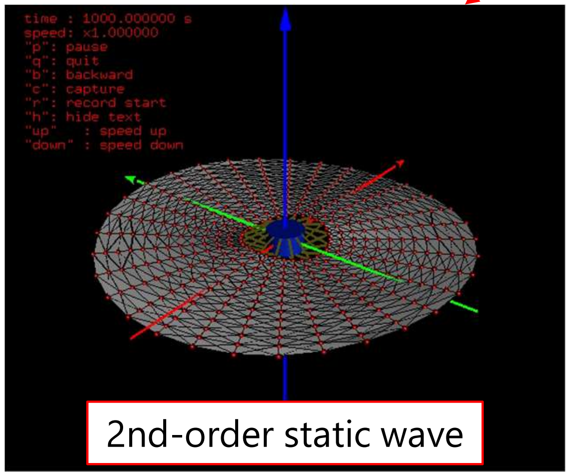
Active Shape Control of Spinning Solar Sails
Various shapes of static waves

Input wave: $w_0(r_a, \theta, t) = \underline{A_0} \cos\{\underline{m_0}(\theta + \Omega t) + \underline{\alpha_0}\}$

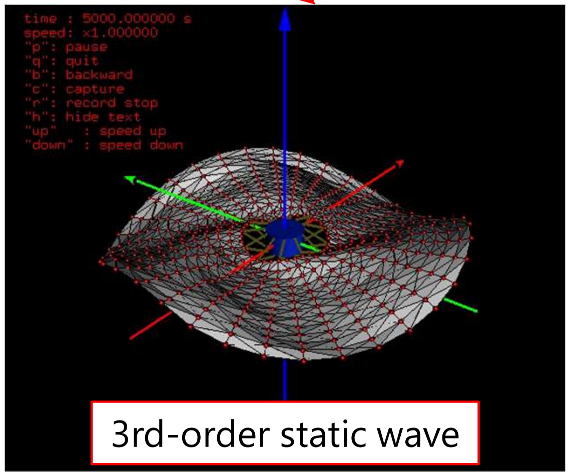
Amplitude Order of wave Phase

Vibration modes of a circular membrane





2nd-order static wave



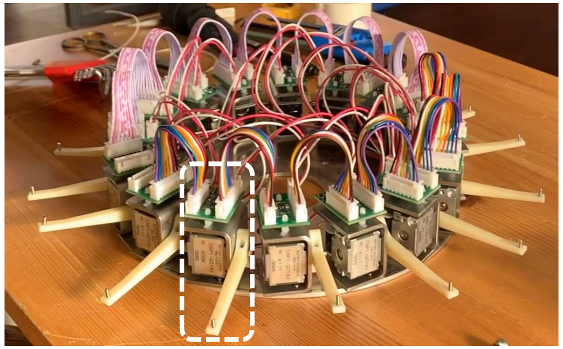
3rd-order static wave

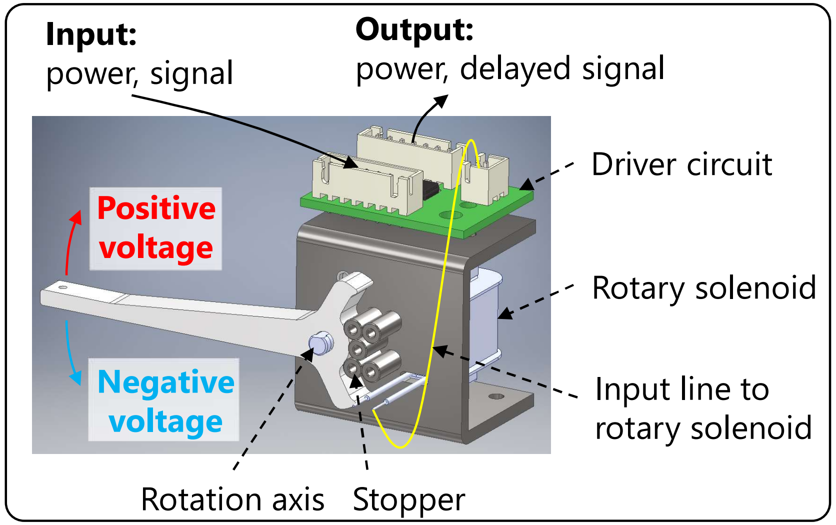
- The shape of the excited wave surface depends on the order (number) of waves.
  - Various shapes can be excited by changing the wavenumbers.
  - The solar sail can maneuver to different shapes actively by switching the wavenumbers.
- The amplitude and phase of the excited wave can also be controlled through A_0 and α_0.

Continuous shape of the solar sail can be controlled actively.

Active Shape Control of Spinning Solar Sails
Ground experiment

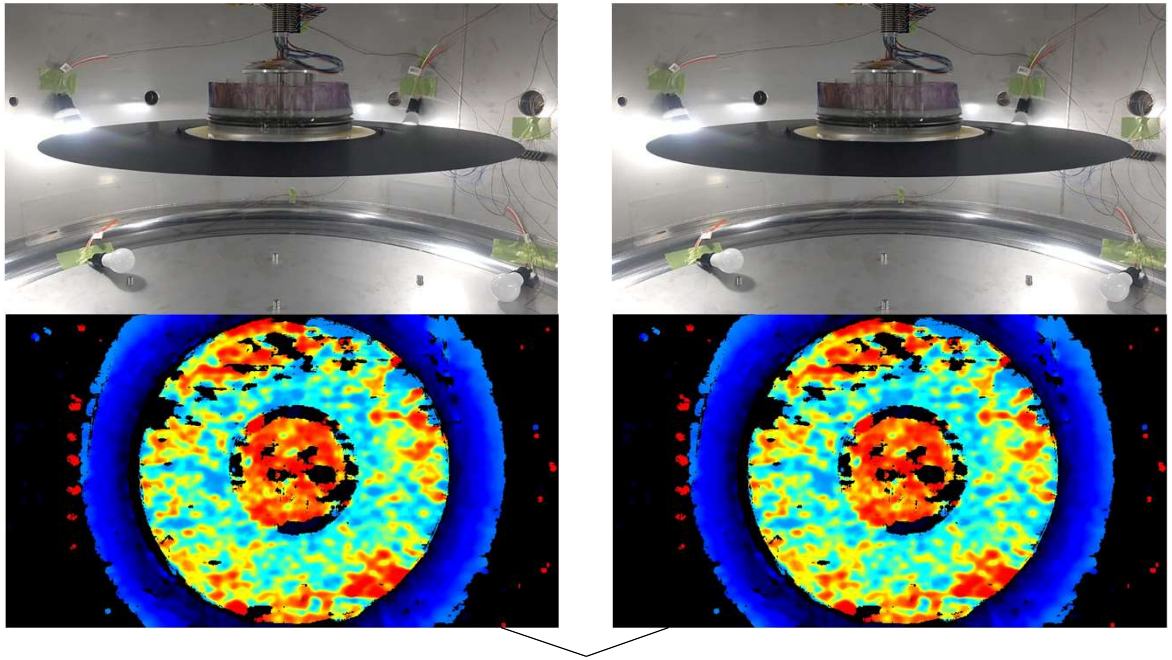
Excitation device using electromagnetic actuators





The proposed method was demonstrated through a ground experiment conducted in a 1-m-class vacuum chamber.

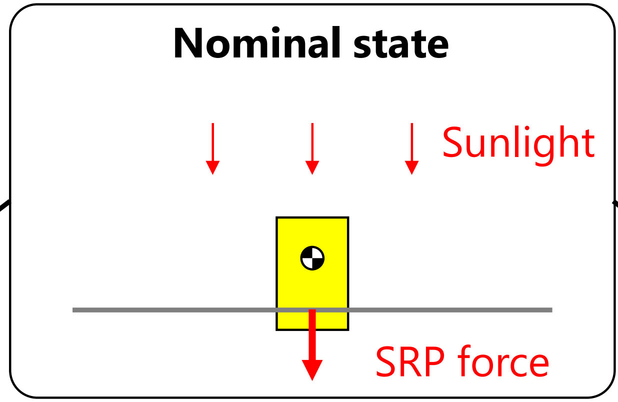
1st-order static wave　　2nd-order static wave

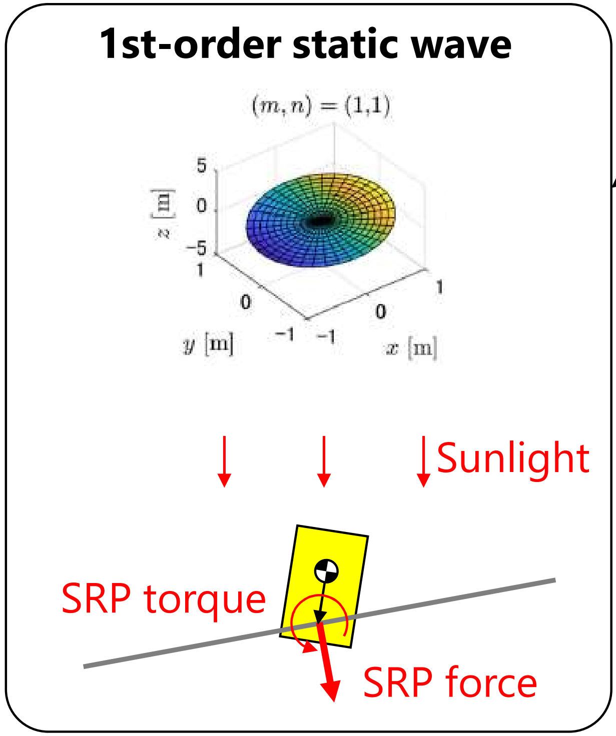


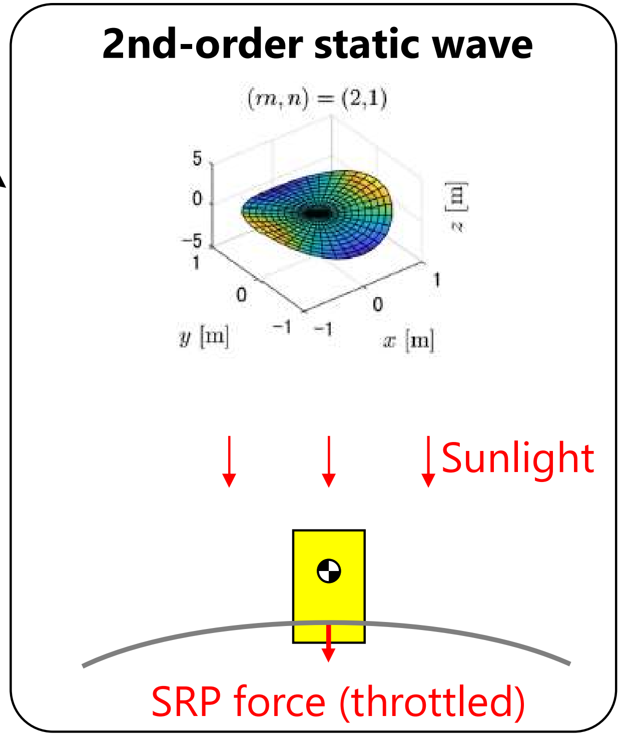
Real-time 3D measurement using a depth camera

Application to Solar Sailing

- Active shape control makes it possible to manipulate **thrust** and **torque** due to SRP for simultaneous orbit-attitude control.







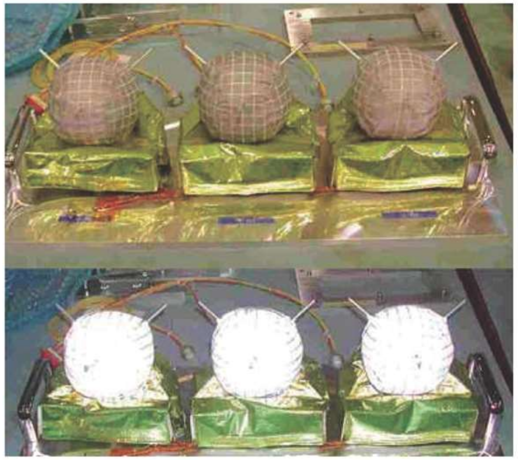
Coupled orbit-attitude-structure motion can be controlled using internal actuators only.

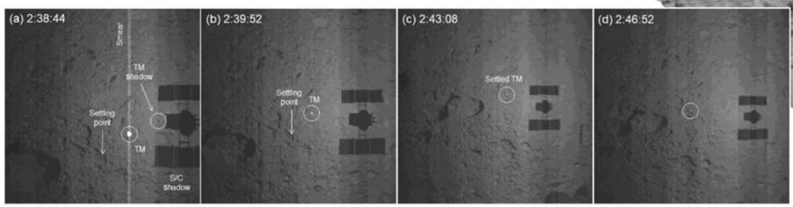
Hayabusa2 – The Asteroid Sample Return Mission

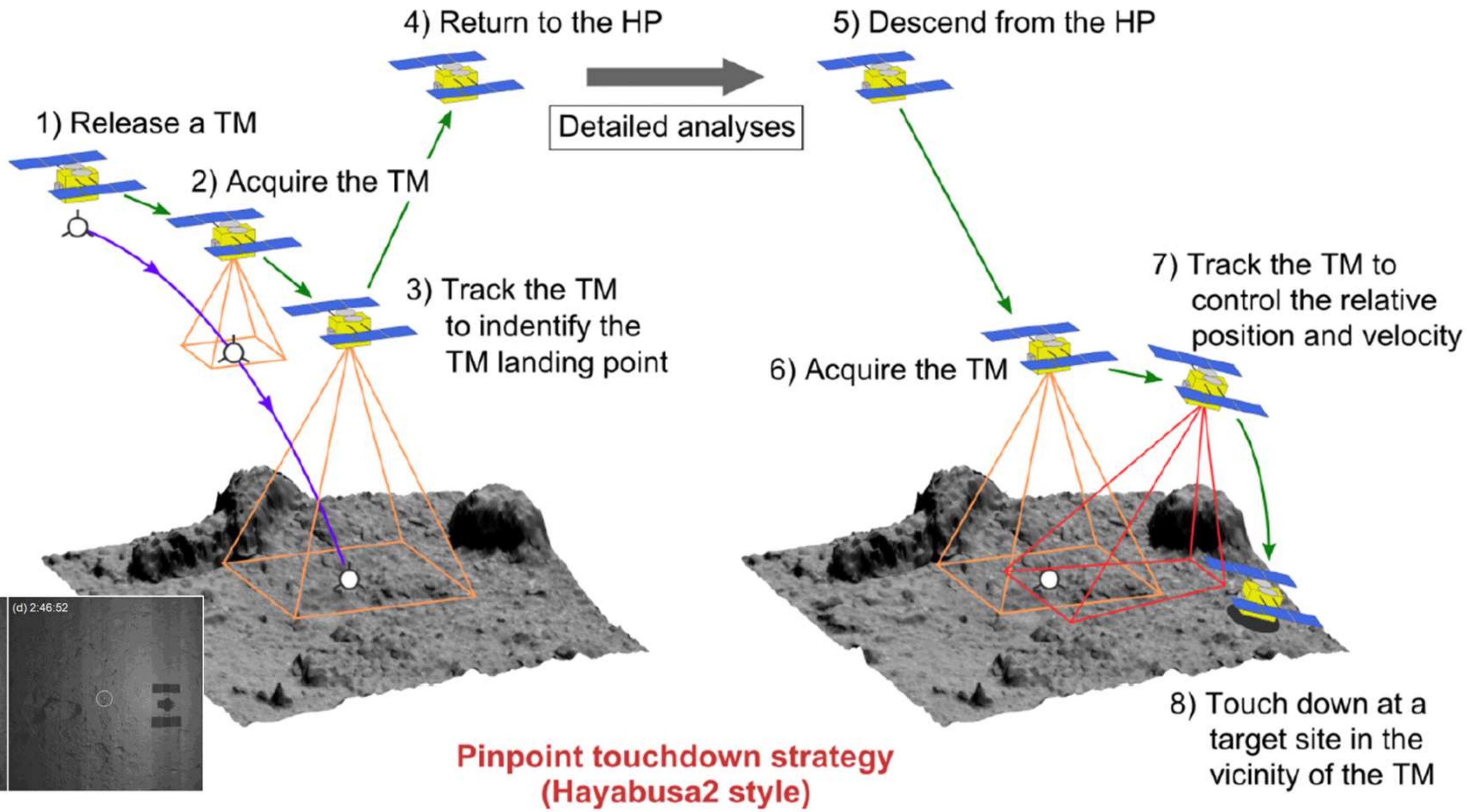
- ✓ Successfully returned samples from the asteroid Ryugu back to Earth in Dec. 2020.
- ✓ Performed two touchdowns on Ryugu, and achieved the landing accuracy of 60 cm.
- ✓ Some deployable payloads were used to enrich the exploration of the asteroid.

Hayabusa2 – The Asteroid Sample Return Mission

- In the Hayabusa2 mission, an artificial marker called target marker played a critical role in the precision landings.



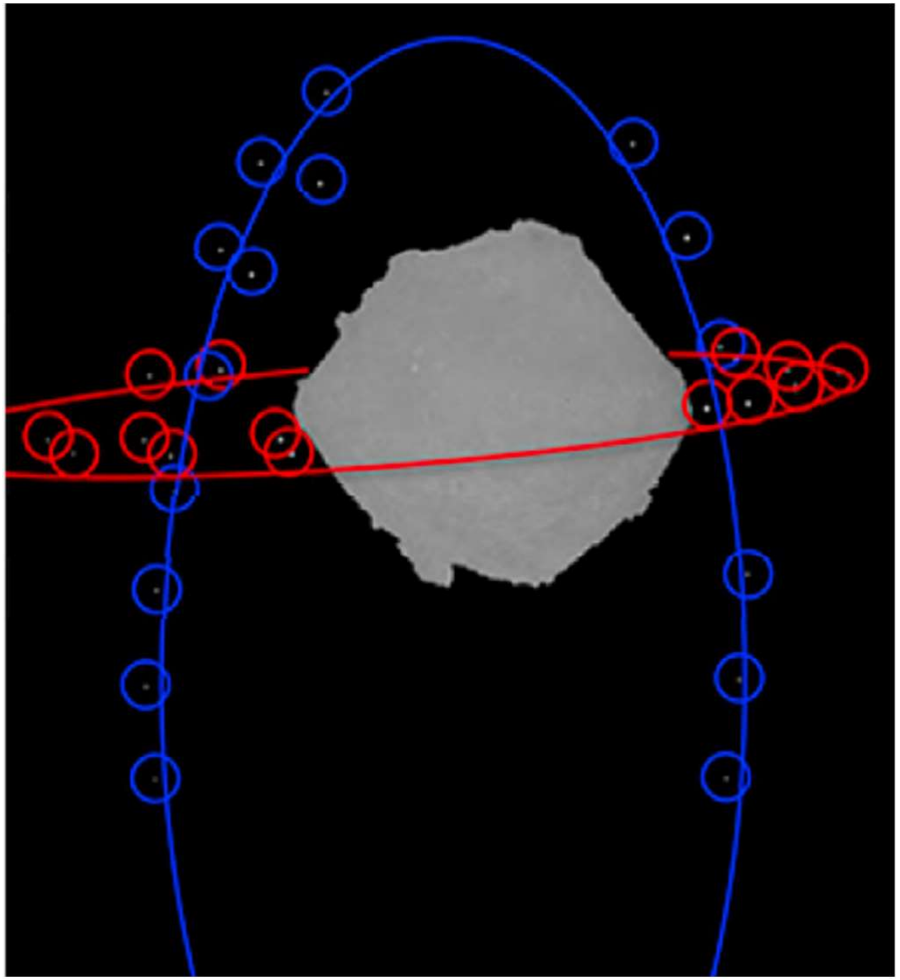




Hayabusa2 – The Asteroid Sample Return Mission

Hayabusa2 – The Asteroid Sample Return Mission

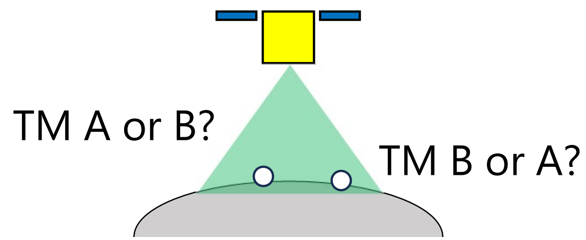
- Hayabusa2 used a hovering method in its proximity operations.
- An orbiting operation was also planned as an option, though it was not realized unfortunately.
- Instead, Hayabusa2 performed an orbiting experiment of deployable payloads including one of remaining target markers, and realized the world's first artificial satellite around a small body.



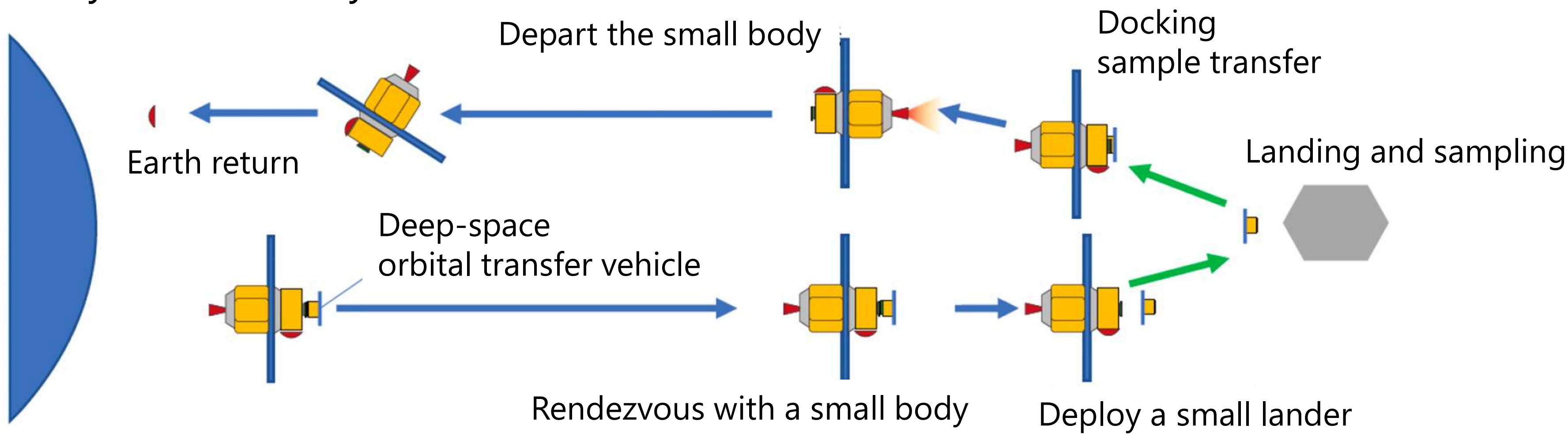
Next-Generation Small-Body Sample Return Mission

Challenges of Hayabusa2

- ✓Risk of performing multiple landings by a single spacecraft.
- ✓Difficulty in detecting target markers from a distant position.
- ✓Difficulty in identifying multiple target markers.

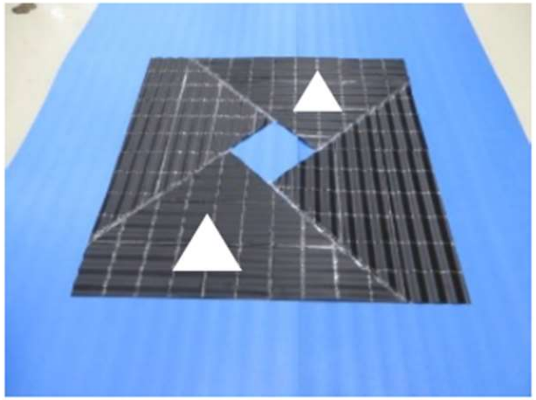


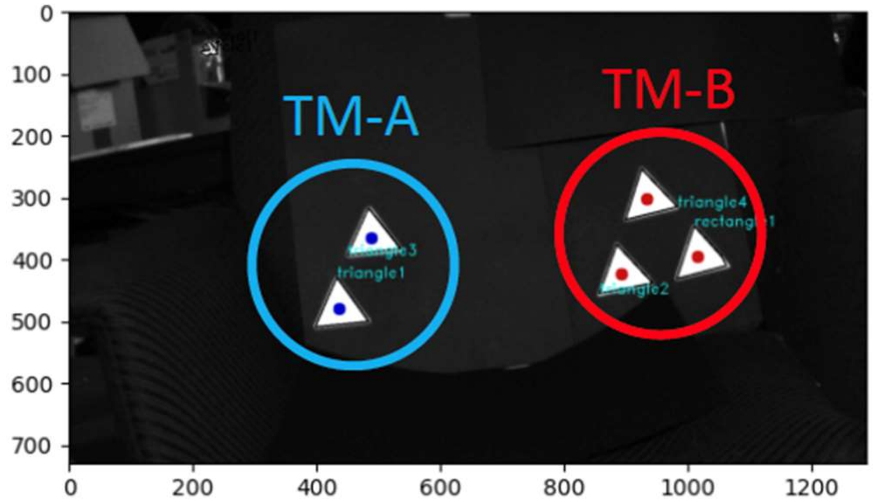
Based on these lessons, we have started the next-generation small-body sample return mission study in this a few years.



Next-Generation Small-Body Sample Return Mission

- Deployable target marker (DTM)
  - A solar sail-like membrane is deployed.
  - DTMs can be detected from a distant position because of the large area and reflective surface of the solar sail.
  - In addition, DTMs make it possible to identify individuals by detecting optical patterns printed on the membrane surface.

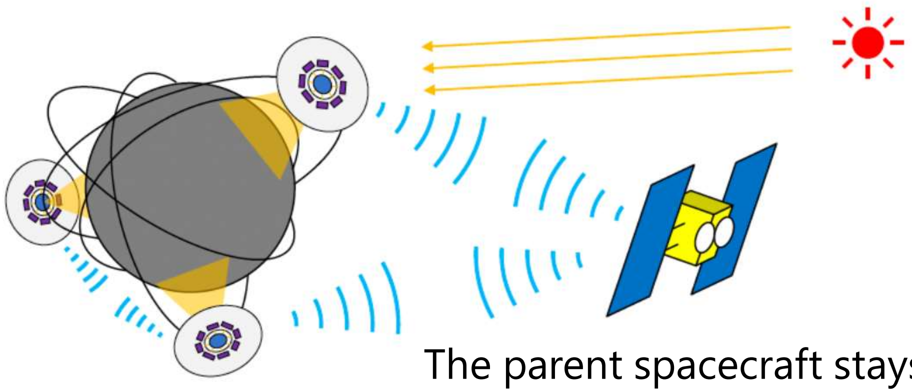




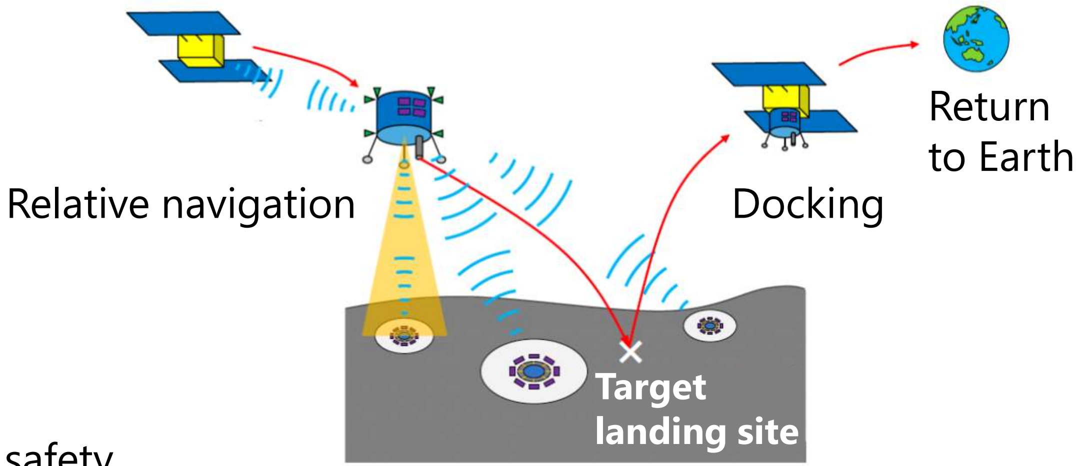
Next-Generation Small-Body Sample Return Mission

Advanced proposal: Active Flying Target Marker (AFTM)

- ✓ Power generation using flexible solar arrays
- ✓ Intercommunication and relative navigation using RF sensors (phased-array antennas).
- ✓ SRP-based orbit maintenance and control.
- ✓ Deorbit through solar sailing to land on the ground.
- ✓ Use as optical and active markers to support the descent and landing of the parent spacecraft.



The parent spacecraft stays at a high altitude to ensure safety.



Application

- ✓ High-resolution global mapping through observations in low-altitude orbits (reconnaissance satellite).
- ✓ Internal structure observation through ground penetrating radars.
- ✓ Seismometer.

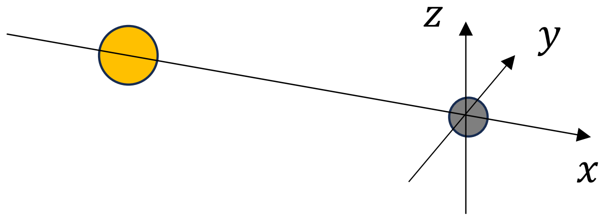
Coupled Orbit-Attitude-Structure Control
Equation of motions

Equation of orbital motion (Hill three-body problem)

$$\ddot{x} - 2n\dot{y} - 3n^2 x = -\mu \frac{x}{r^3} + a_x$$

$$\ddot{y} + 2n\dot{x} = -\mu \frac{y}{r^3} + a_y$$

$$\ddot{z} + n^2 z = -\mu \frac{z}{r^3} + a_z$$



Euler's equation of motion for a spinning solar sail

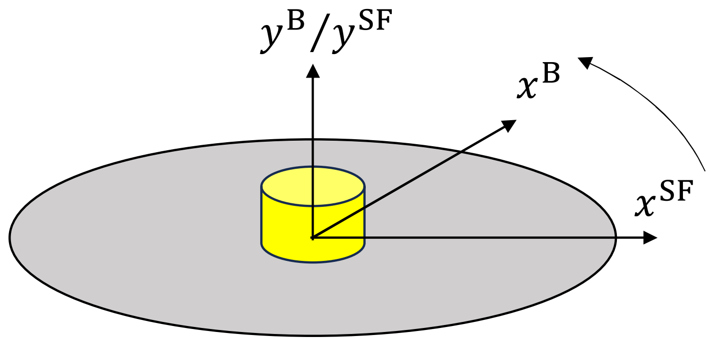
$$\boldsymbol{I}\dot{\boldsymbol{\omega}} + \tilde{\boldsymbol{\omega}} \times \boldsymbol{I}\boldsymbol{\omega} = \boldsymbol{T}$$

⇒ Equation of motion of long-period attitude dynamics

$$\dot{\psi} = \frac{T_x}{(I_s + I_b)\Omega} - \omega_s, \quad \dot{\phi} = \frac{T_y}{(I_s + I_b)\Omega}$$

Spin rate

In-plane Sun angle — Out-of-plane Sun angle



Σ^{B}: Body-fixed frame
Σ^{SF}: Spin-free frame

Equation of motion of the sail deformation

$$\rho r \frac{\partial^2 w}{\partial t^2} = \frac{\partial}{\partial r}\left(\sigma_r \frac{\partial w}{\partial r} r\right) + \frac{\partial}{\partial \theta}\left(\sigma_\theta \frac{\partial w}{r \partial \theta}\right)$$

$$\Rightarrow w(r, \theta, t) = \sum_m A_m R_{mn}(r) \cos\{m(\theta + \Omega t) + \alpha_m\}$$

Coupled Orbit-Attitude-Structure Control
Orbit maintenance around small bodies

Orbit control

The orbital motion is controlled so that the spacecraft tracks the reference orbit.

Linearized equation of motion:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u}$$

Reference orbit:

$$\dot{\boldsymbol{x}}_r = \boldsymbol{A}\boldsymbol{x}_r$$

Deviation from the reference:

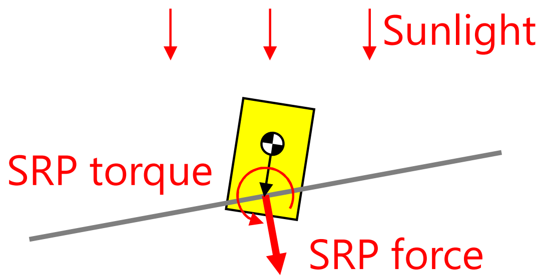
$$\dot{\boldsymbol{e}} = \boldsymbol{A}\boldsymbol{e} + \boldsymbol{B}\boldsymbol{u}$$

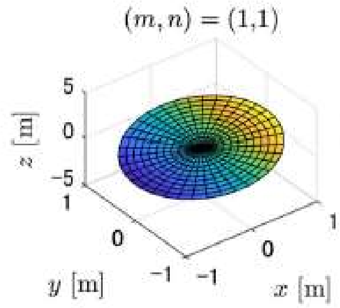
Feedback control using linear quadratic regulator (LQR):

$$\text{minimize } J = \int_0^\infty (\boldsymbol{e}^T \boldsymbol{Q}\boldsymbol{e} + \boldsymbol{u}^T \boldsymbol{R}\boldsymbol{u})\mathrm{d}t$$
$$\Rightarrow \boldsymbol{u} = \boldsymbol{K}\boldsymbol{e} = [\phi, \psi]^T$$

Attitude control

The 1st-order static wave is used for attitude control.





Controlled deformation:

$$w^{\mathrm{I}}(r, \theta, t) = A_1 r \cos(\theta + \alpha_1)$$

SRP force and torque:

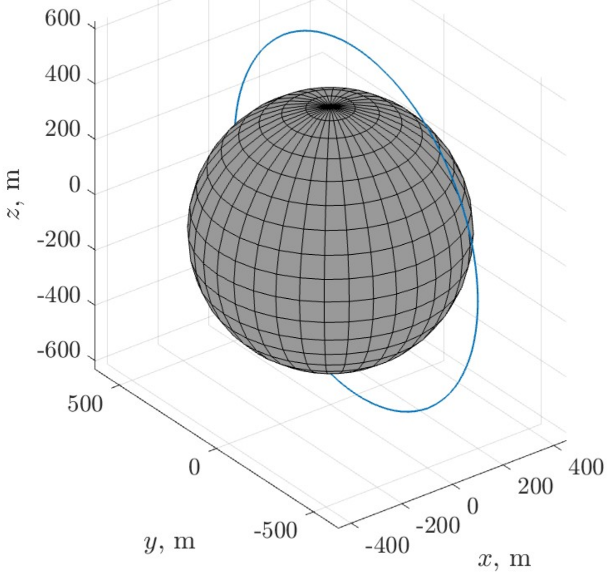
$$\boldsymbol{F} = \boldsymbol{F}(A_1, \alpha_1), \qquad \boldsymbol{T} = \boldsymbol{T}(A_1, \alpha_1)$$

PD control is applied such that the target attitude is tracked.

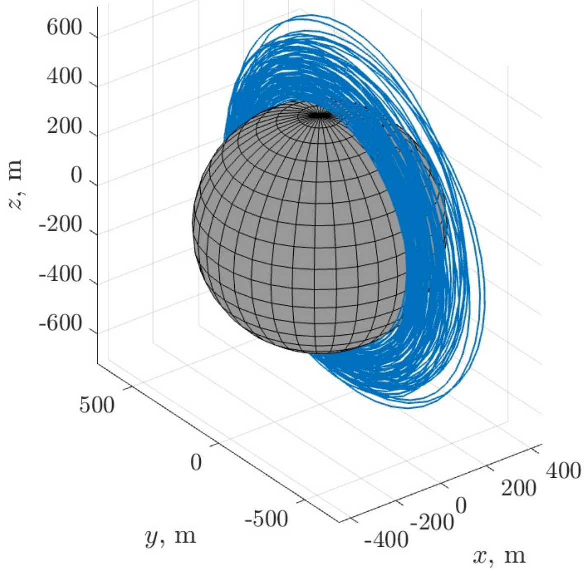
Coupled Orbit-Attitude-Structure Control
Orbit maintenance around small bodies

- A terminator orbit is given as the reference (target) orbit.
- Although terminator orbits are known to be stable, the spacecraft may impact or escape from the small body if there is orbit insertion error.
- The target orbit can be maintained through solar sailing under active shape control.

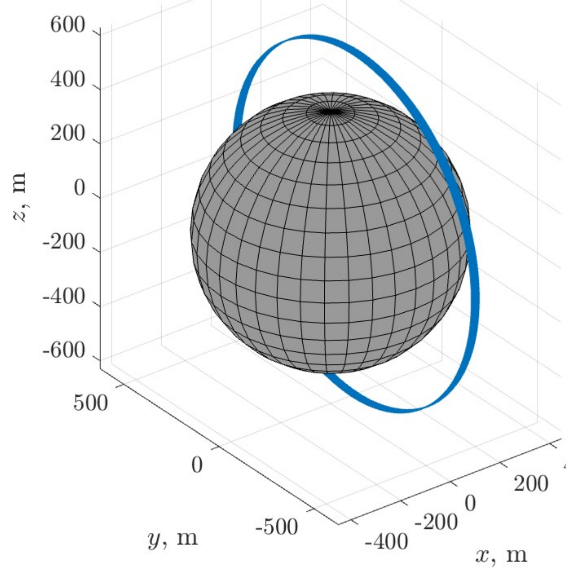
Reference



With insertion error

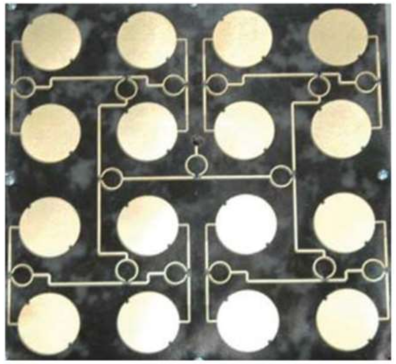


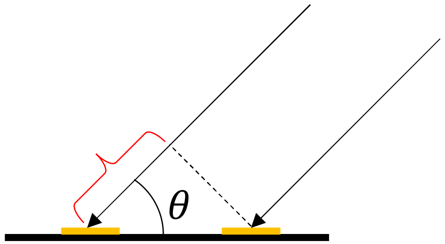
With insertion error and control



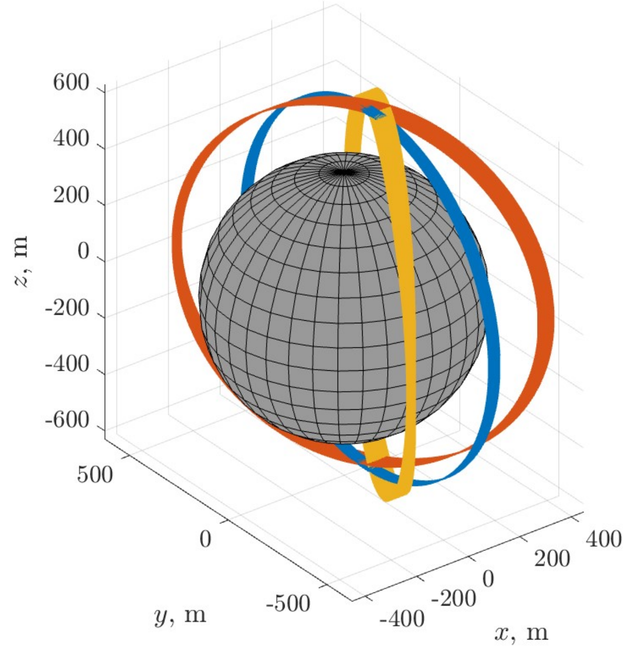
Coupled Orbit-Attitude-Structure Control
Constellation around small bodies

- Multiple AFTMs are deployed in different orbits around the small body.
- Phased-array antennas mounted on the AFTMs are used for relative navigation.
  - In addition to the range-and-range-rate (RARR) measurement, the RF sensors have the retrodirective function that observes the direction where the signal comes from.
  - The relative positions of the AFTMs can be estimated using extended Kalman filter.





Signal direction can be detected from the time difference of received signals for the antenna arrays.



Summary

- Active shape control method for spinning solar sails was presented.
  - The proposed method excites vibrations to control the whole (continuous) shape of the membrane.
  - A hardware system assuming flight demonstration is under development.
- Active deformation can be applied to simultaneous orbit-attitude-structure control.
- A framework of constellation around small bodies using active flying target markers was proposed.
  - CubeSats equipped with solar sails are deployed in different orbits around the small body.
  - Advanced science such as high-resolution global mapping, internal structure measurements via ground penetrating radars, and seismometer can be realized.
  - A brief simulation was carried out to demonstrate the basic parts of the proposed idea.