The Future of Space Exploration using Deployable Structures in Japan: Challenges and Opportunities

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Space Structure Systems

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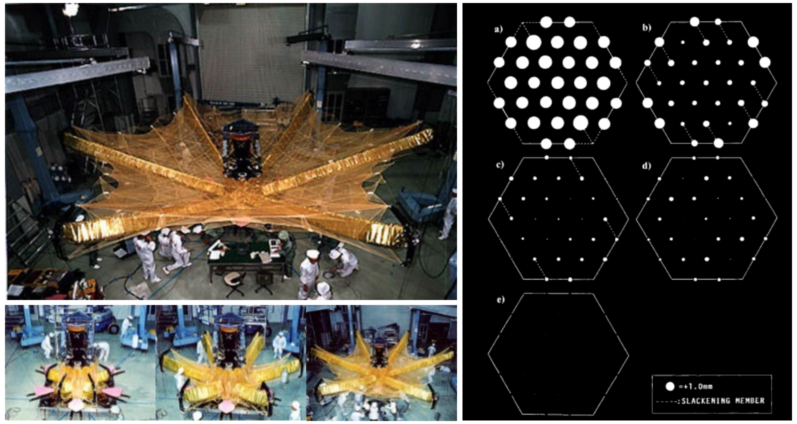
   my research experience on deployable structures)
2. Deployable structures for space science mission
   deployable structures used or will be used in space science missions
3. What are the problems?
   key technical problems to realize the mission and achieve the mission success using deployable structures
   our current challenges to realize the cutting-edge space exploration missions by solving those problems

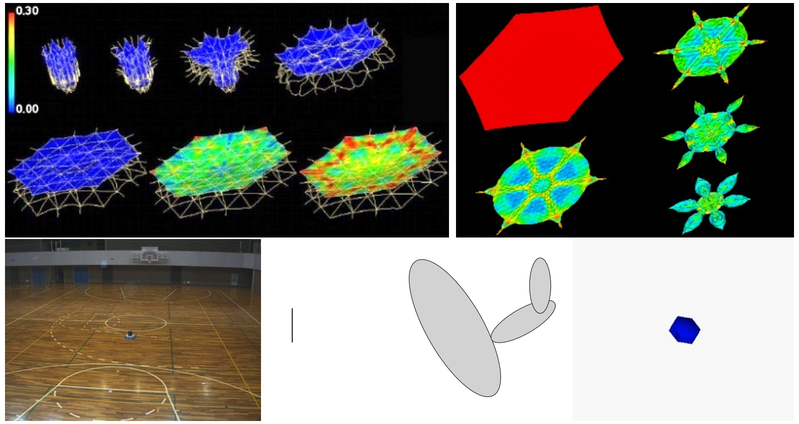
Self-Introduction

Analysis of deformation of cable-mesh antenna



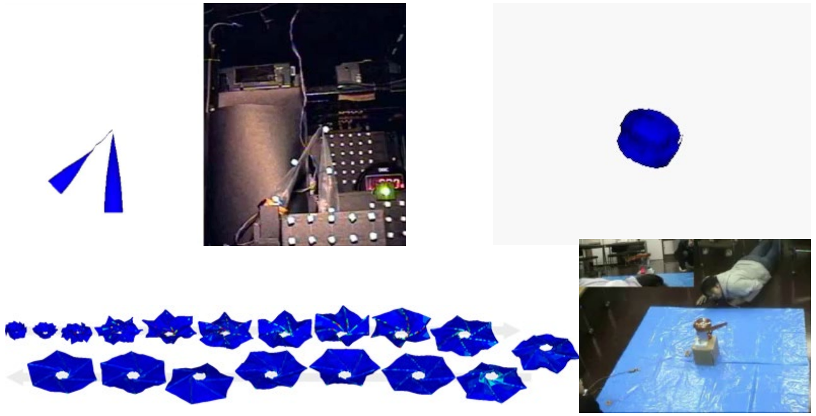
On-orbit/pre-launch shape adjustment to satisfy the requirement of surface accuracy

Formulation of structure-conserving scheme of gossamer structure



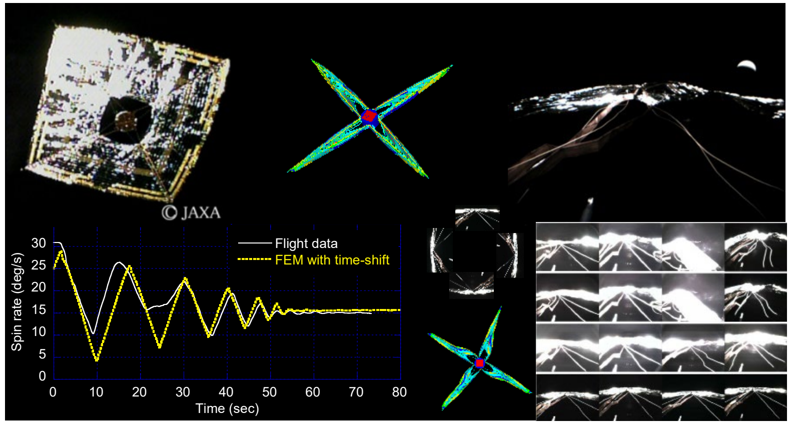
Deployment and folding of membrane under no external load

Analysis of dynamic interaction between membrane and injected gas



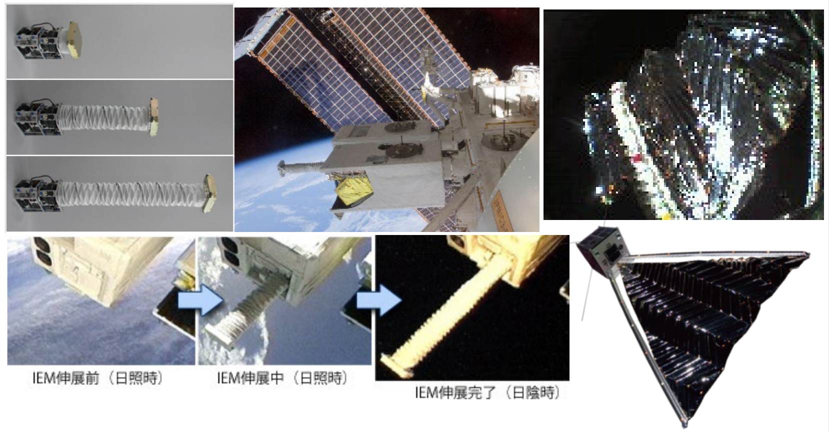
Deployment of inflatable membrane structure

Prediction of deployment of solar sail IKAROS



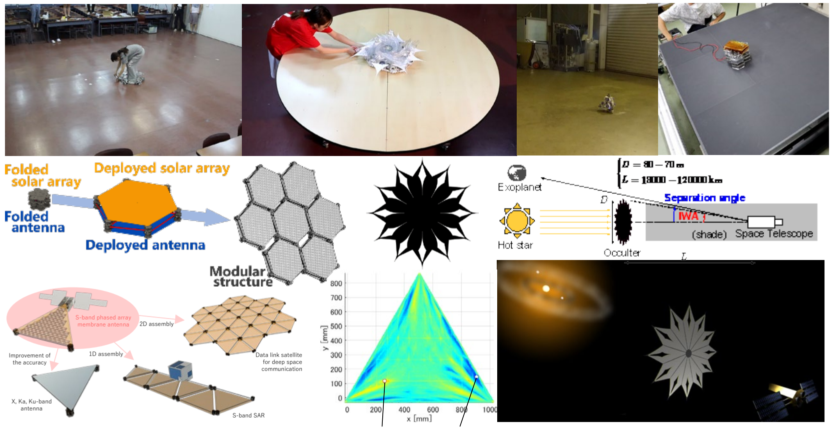
Multi-body dynamics of gossamer structure and rigid body

On-orbit demonstration of inflatable structure



Mission assurance of deployable structure in space

Space utilization of self-deployable membrane truss

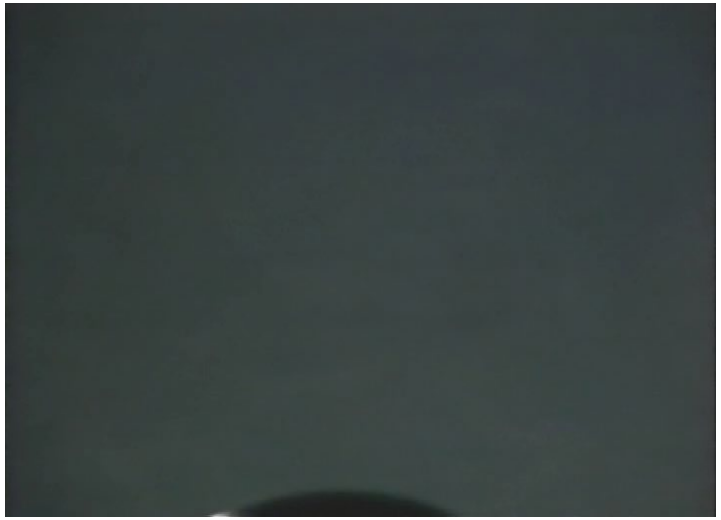
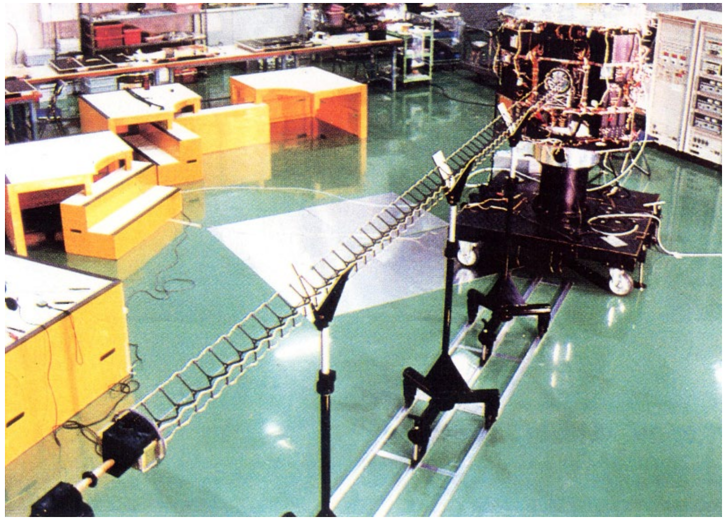


Design method of gossamer structure for reliable deployment and high shape accuracy

2. Deployable structures for space science mission

Deployable structures for space science mission

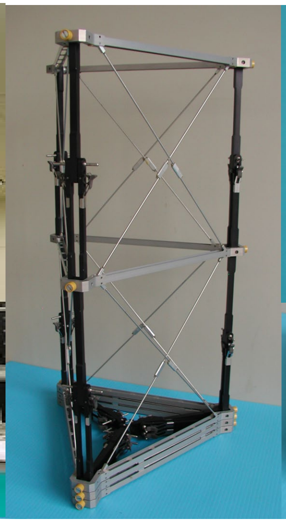
★Extensible mast/boom (conventional)

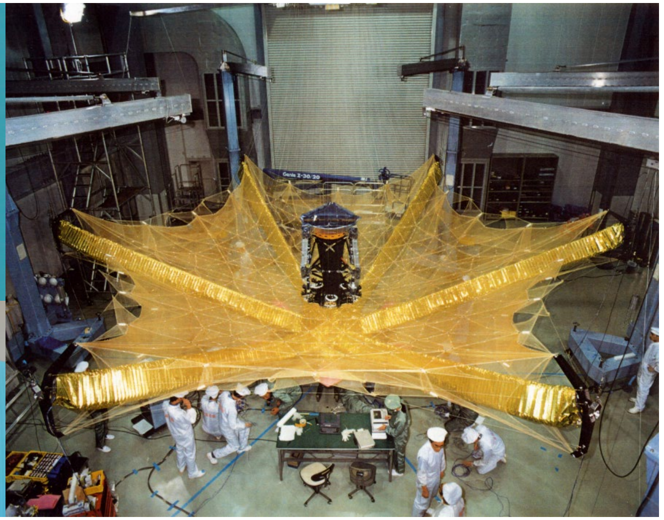
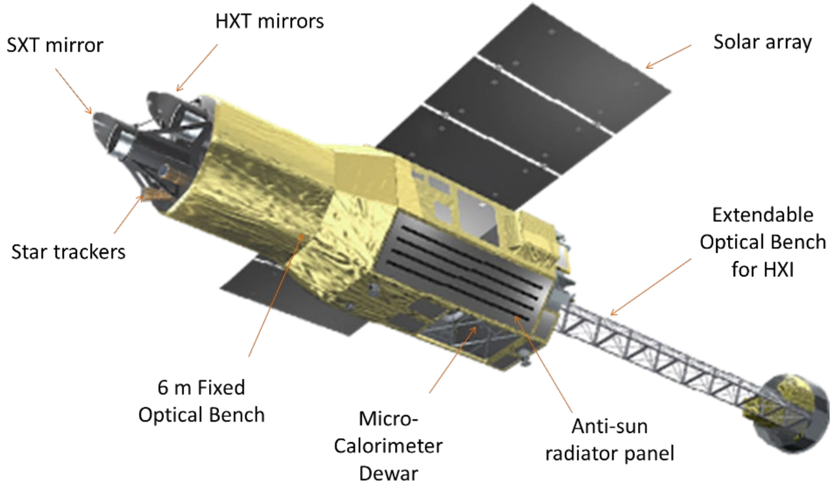



- Lightweight flexible mast
- High stiffness extensible truss

⬇

Currently, much lighter mast with higher storage efficiency is desired in space science mission

Deployable structures for space science mission

★Extensible mast/boom (current)

- Lightweight flexible mast
- High stiffness extensible truss

⬇

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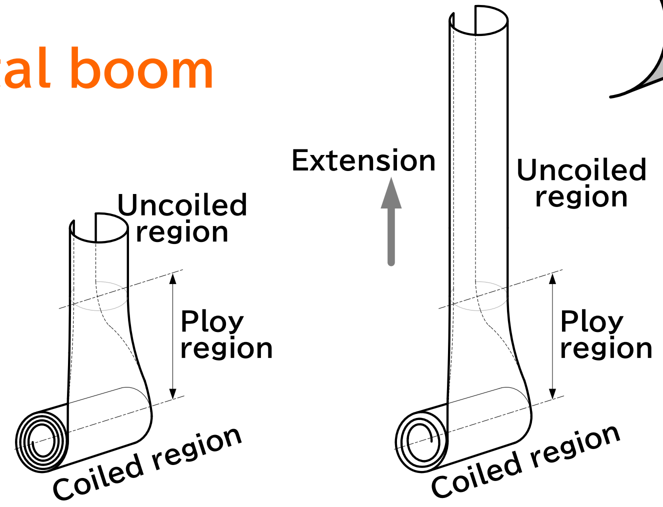
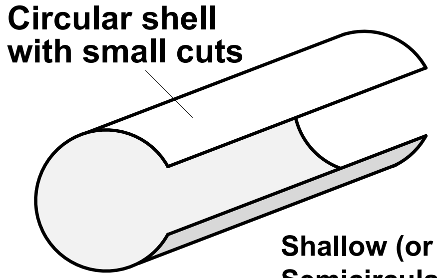
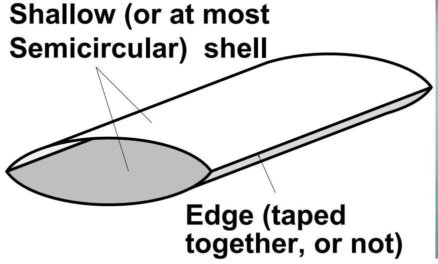
⬇

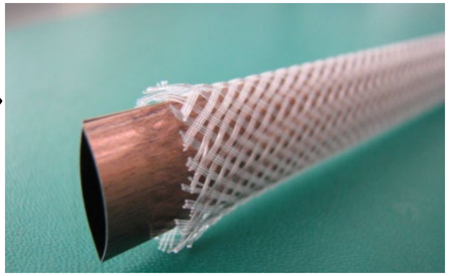
Thin-walled CFRP or metal boom that can be rolled up.

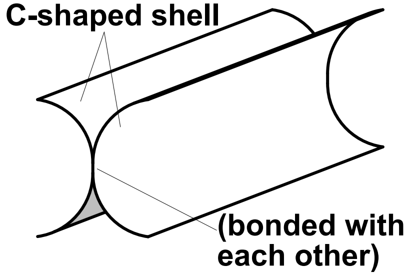
- The boom is extended by the motors or without any assistance (self-extension)

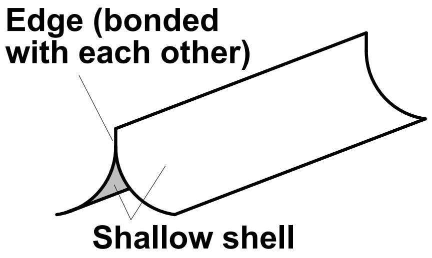


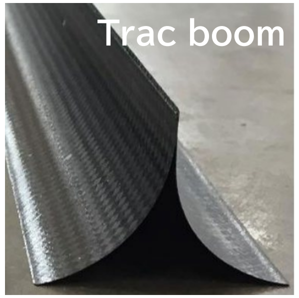


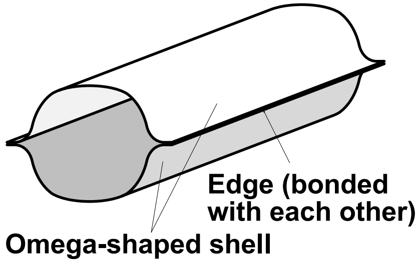


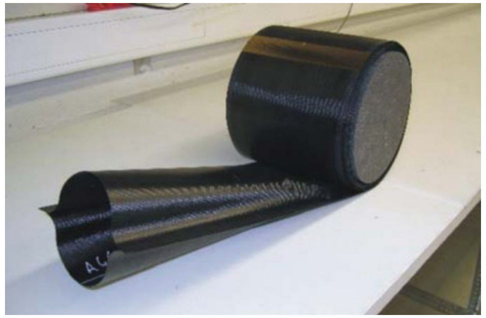








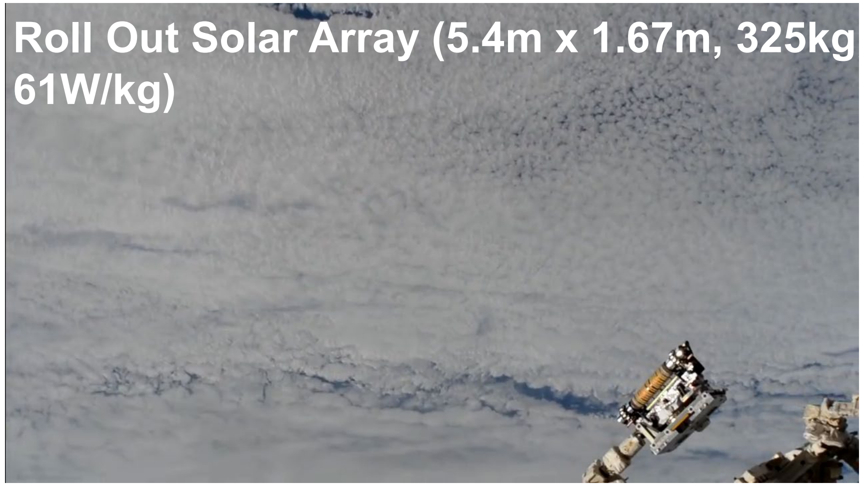




Deployable structures for space science mission

★Extensible mast/boom (current)

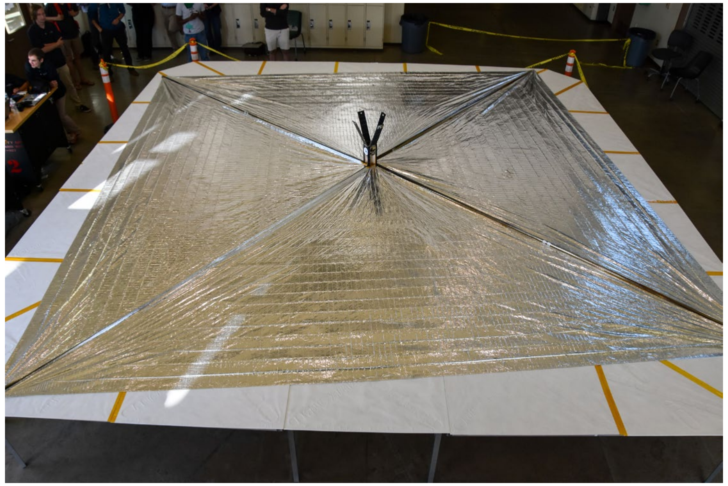
ROSA (2017)

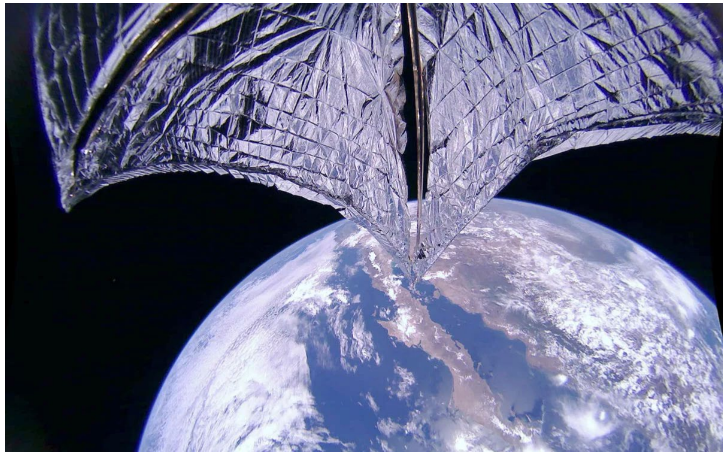


DART (2021)

- US (NASA) has studied on "high strain composite", and the self-extensible open cross-section boom and trac boom have already used in space.

LightSail 2 (2019)





Deployable structures for space science mission

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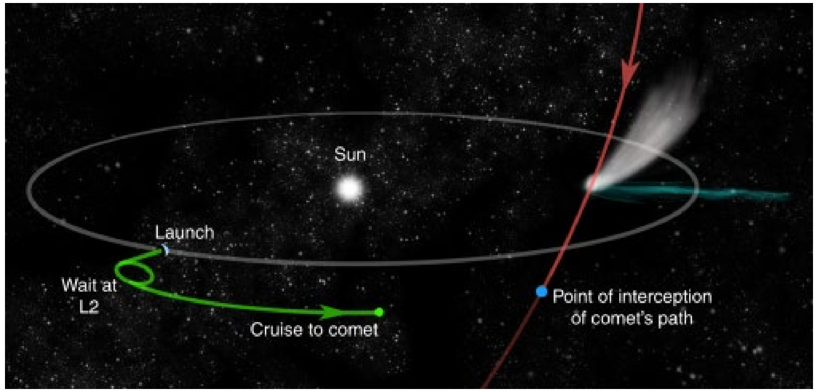
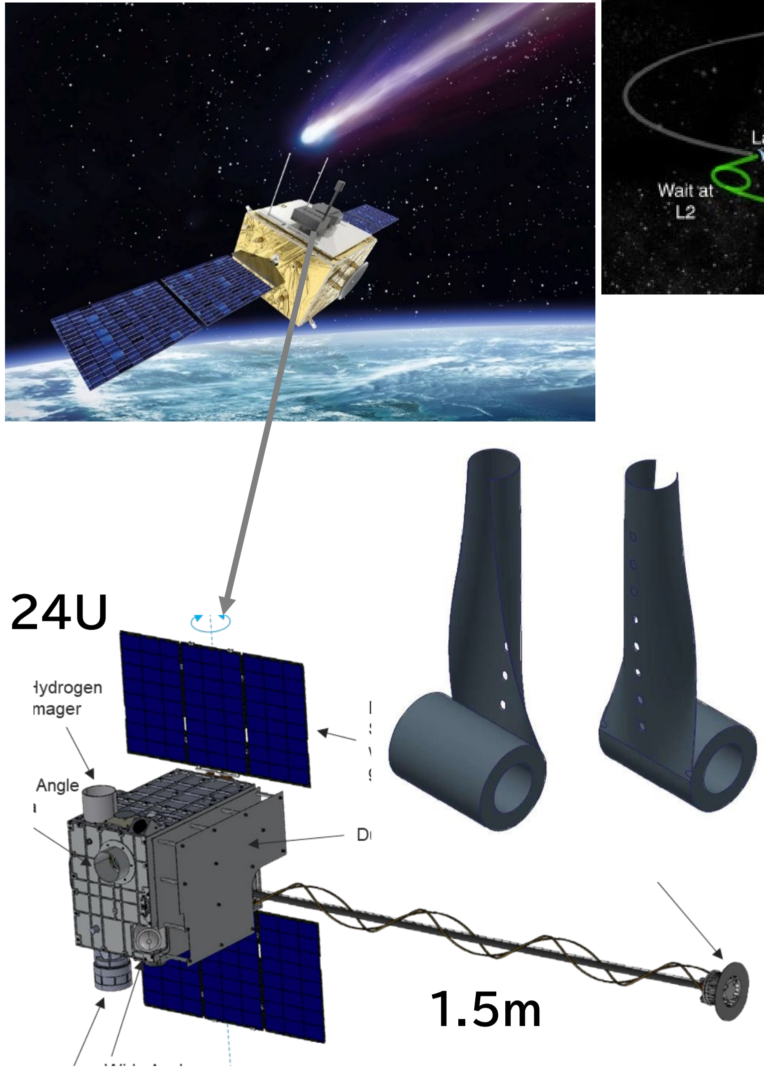
- ESA-JAXA joint mission "Comet Interceptor" has a daughter spacecraft "B1" that has an extensible boom to keep the distance between the spacecraft and the magnetic sensor.
- The CFRP bi-stable boom is adopted as the extensible boom, which is the first space science mission for JAXA to use such kind of boom.



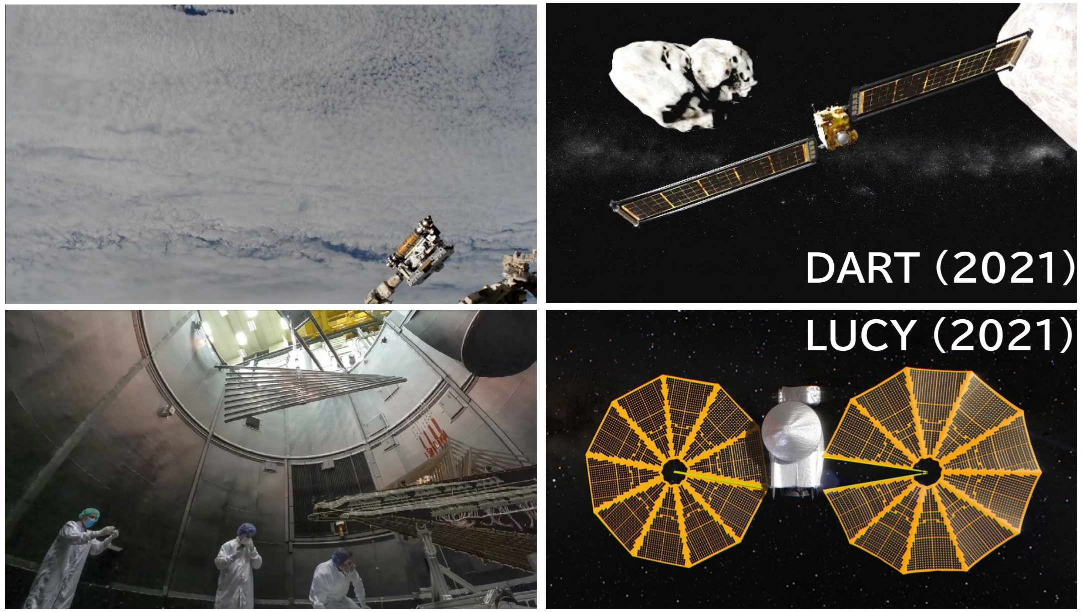


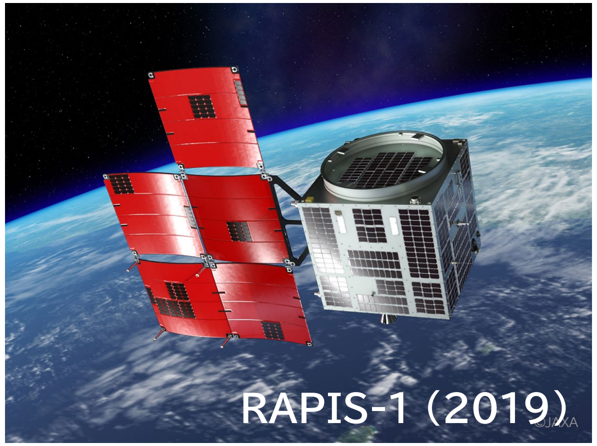
Space Structure Systems

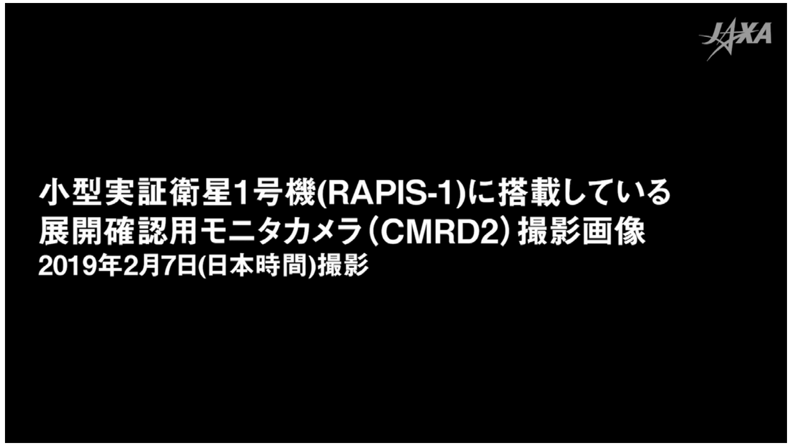
Deployable structures for space science mission

★Solar array

- Lightweight large solar array panel (SAP) is desired for the deep space exploration mission.
- The most efficient SAP is currently about 150W/kg at 1AU.
- Our target is 200W/kg (or 300kg/W) including the deployment mechanisms.







Deployable structures for space science mission

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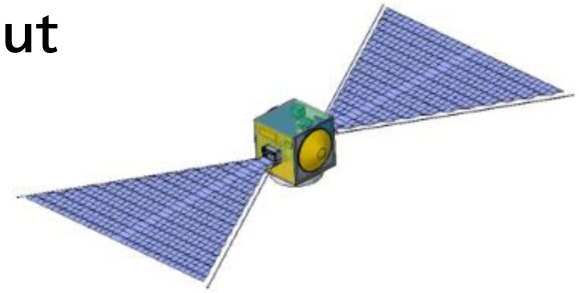
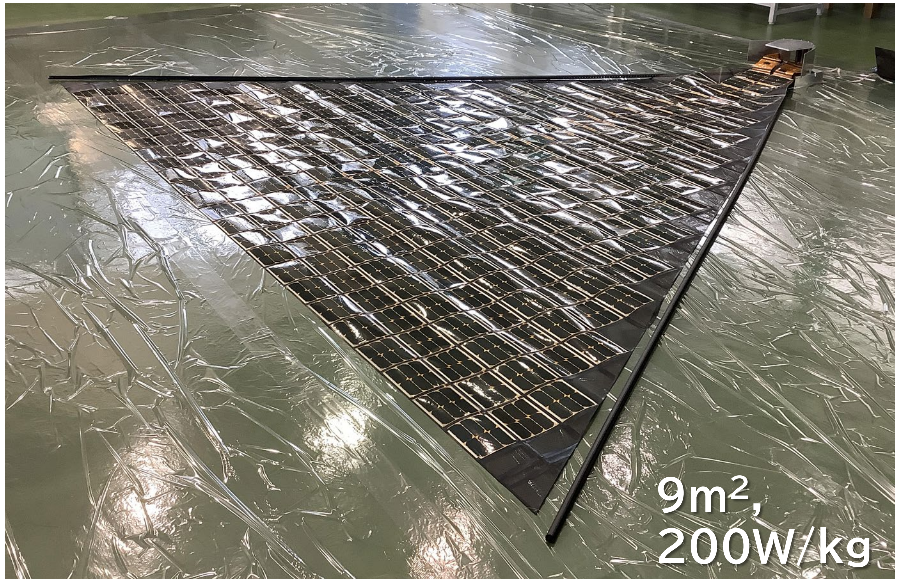
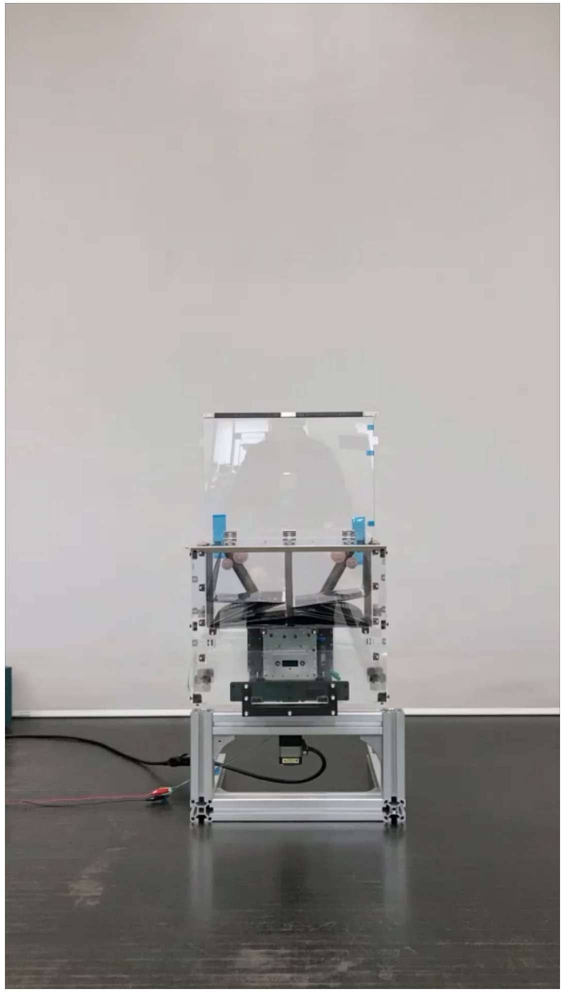
Outer planet explorer



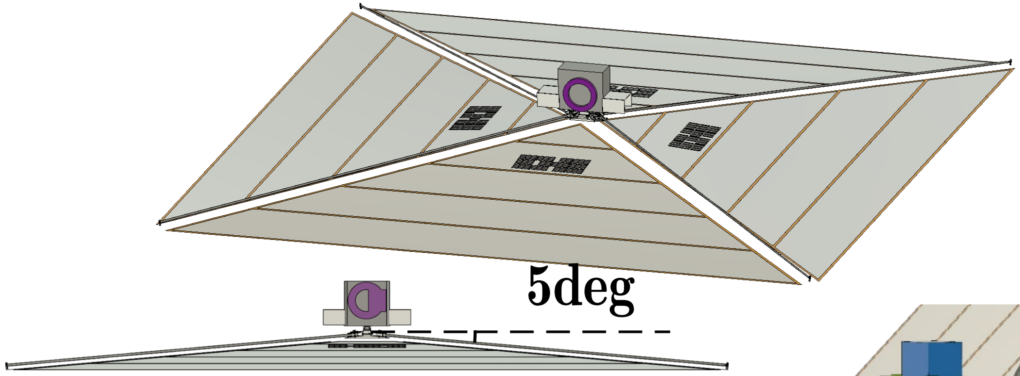


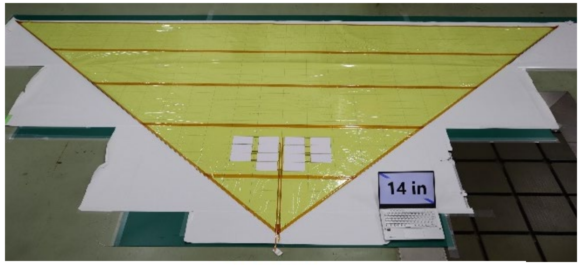


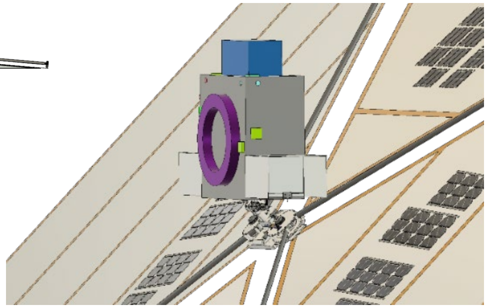
Deployable structures for space science mission

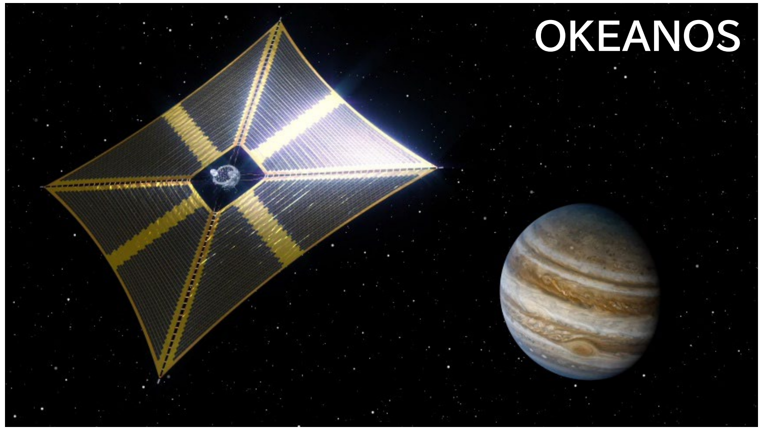
★Solar Power Sail

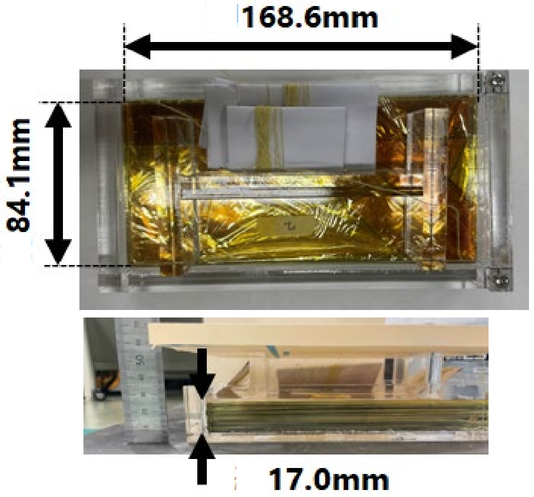
- Solar Power Sail is a spacecraft that has two propulsion system, i.e., photon propulsion system (solar sail) and electric propulsion system such as ion engine.
- JAXA had been researching on 40m class solar power sail “OKEANOS”, which is suspended now.
- Tokyo Tech team (Prof. Chujo) and ISAS are now studying on micro solar power sail with 4.9m x 4.9m sail.

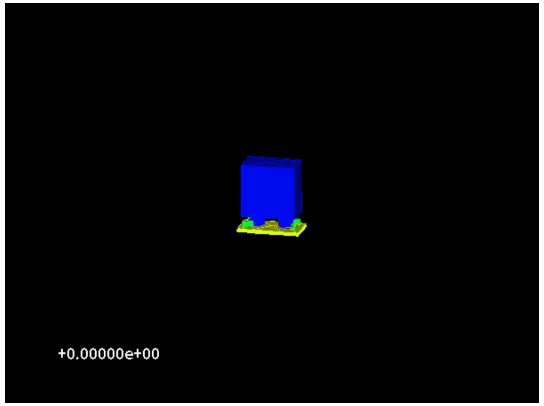










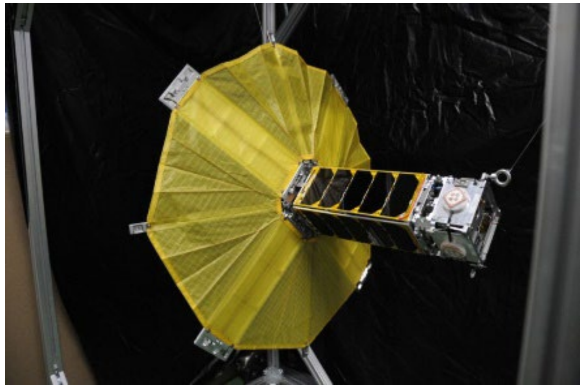


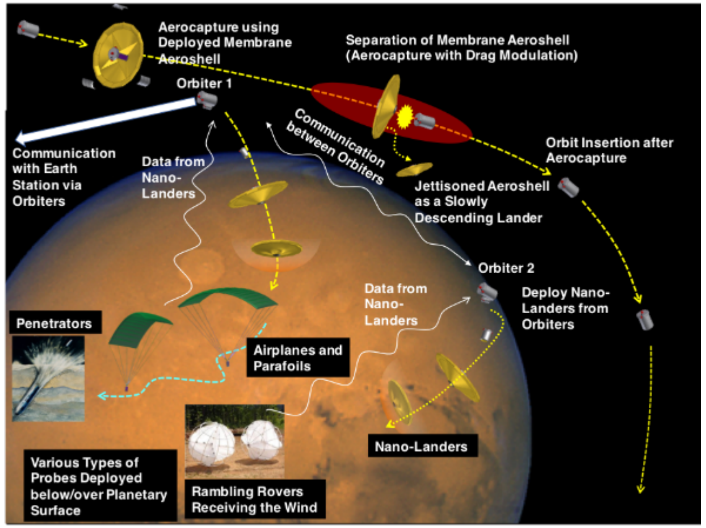
Deployable structures for space science mission

★Aeroshell

- Prof. Suzuki (U. Tokyo), Prof. Yamada (ISAS), and their team have been developing aeroshells for atmospheric entry, which is the primary candidate of the entry system of future Mars landing mission of JAXA.

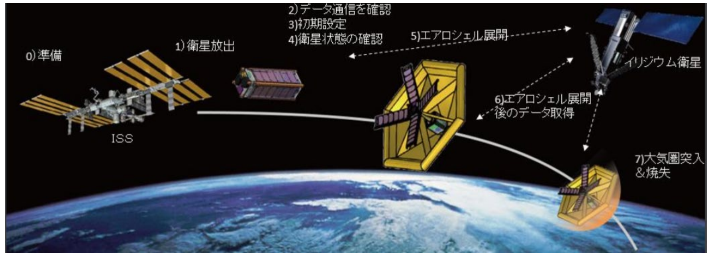
BEAK (2023?)

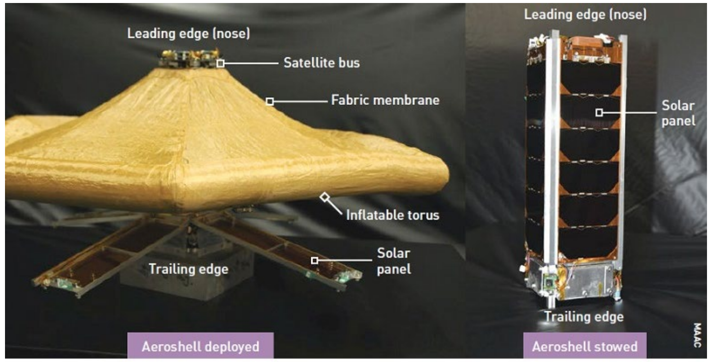


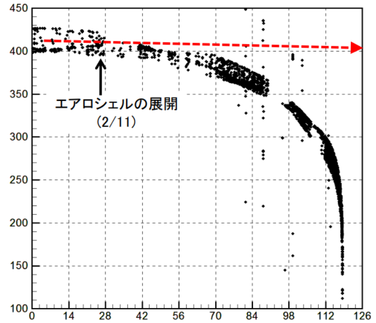


Mars landing mission (3.5m aeroshell?)

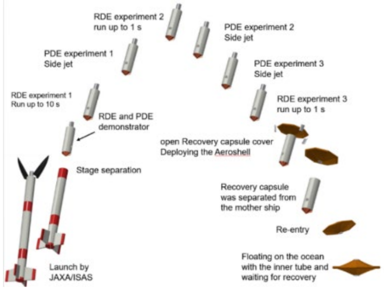
EGG (2017, 0.8m aeroshell)







RATS (2021, 1.2m)

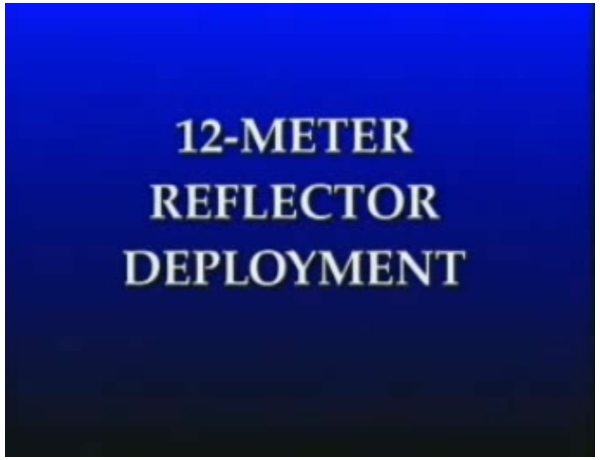


NASA LOFTID (2022, 6m)

3. What are the problems?

What are the problems?

★Verification of the deployment system on the ground (before launch) to guarantee the success of the deployment



- The motion of the gossamer structure is quite sensitive to the external force, e.g., gravity and aerodynamic drag.
- So, the motion in atmosphere under gravity is different from that in space.
- Large structure, e.g., ten meters or larger, is not available for the micro-gravity experiment using the airplane, nor the experiment in the vacuum chamber.
- Even if the structure is small, it is difficult to conduct the experiment in vacuum and micro-gravity environment simultaneously.
- Space demonstration or highly fidelity numerical simulation is necessary?

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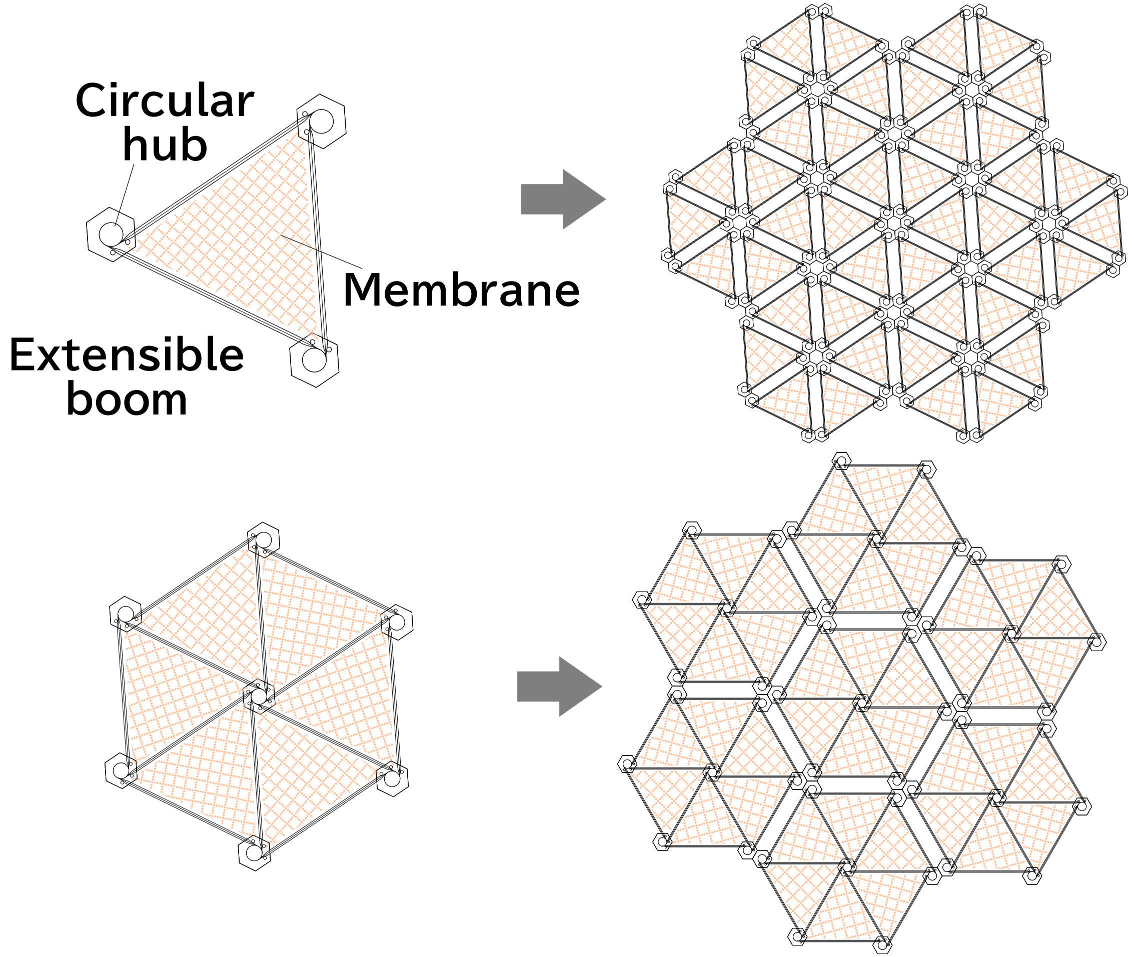

Modular structure is one of the solutions?

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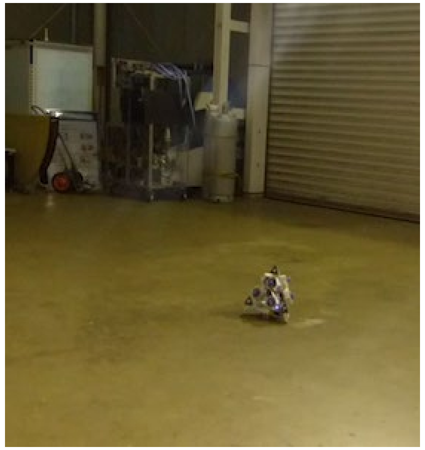

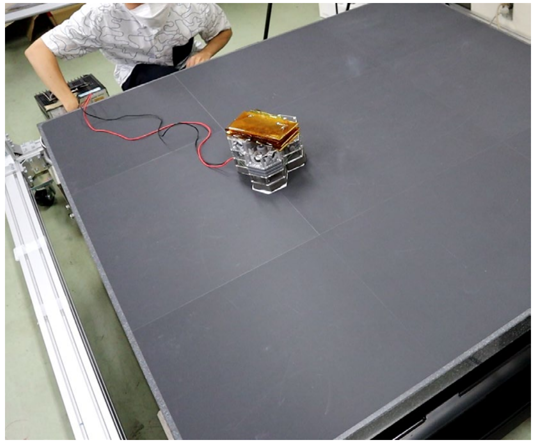

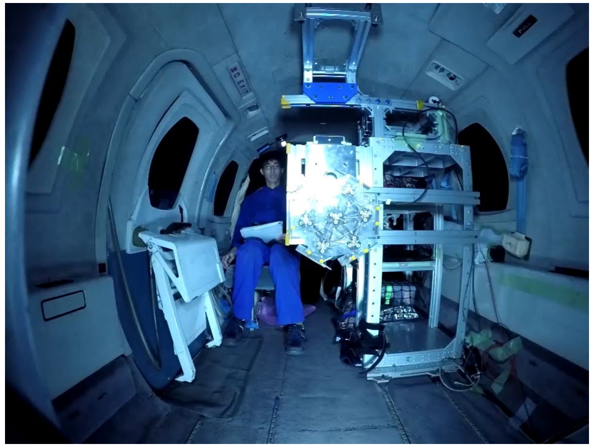

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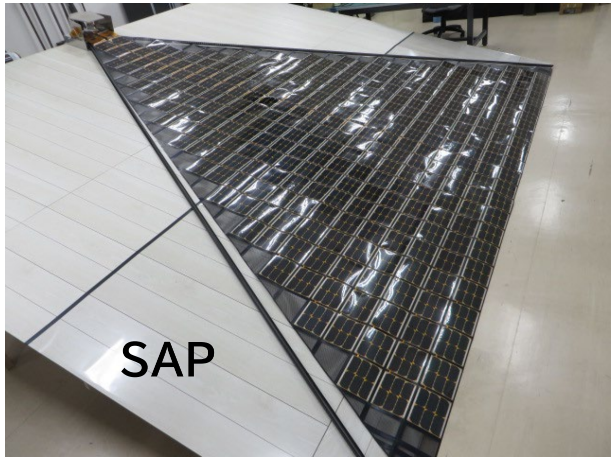
Self-deployable structure is suitable for space mission?

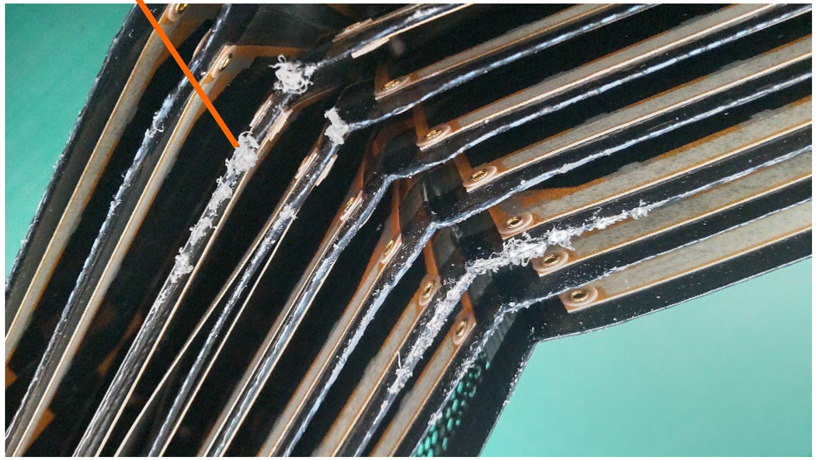
What are the problems?

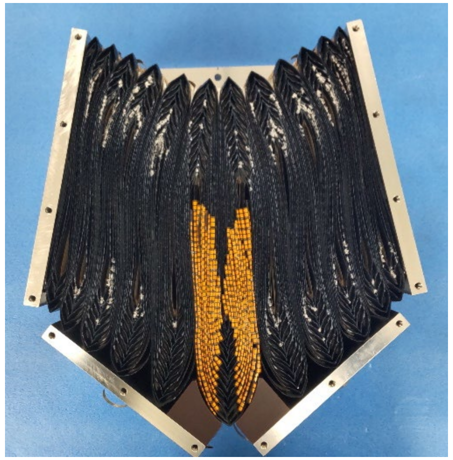
★Launch environment (vibration)

- If some device is attached on a membrane film and the film is folded into small volume, the strength of the fold line is low, so that the fold line is often hurt after vibration test.
- The hold-release mechanism of a flexible structure, e.g., folded membrane structure, is one of the key technology.
- If the hold is too strong, the membrane may be

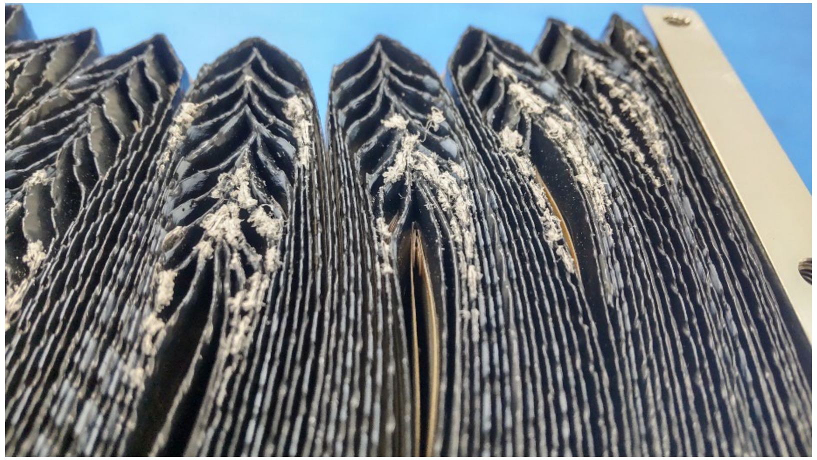


The film rubbed against the other film?





Stored configuration



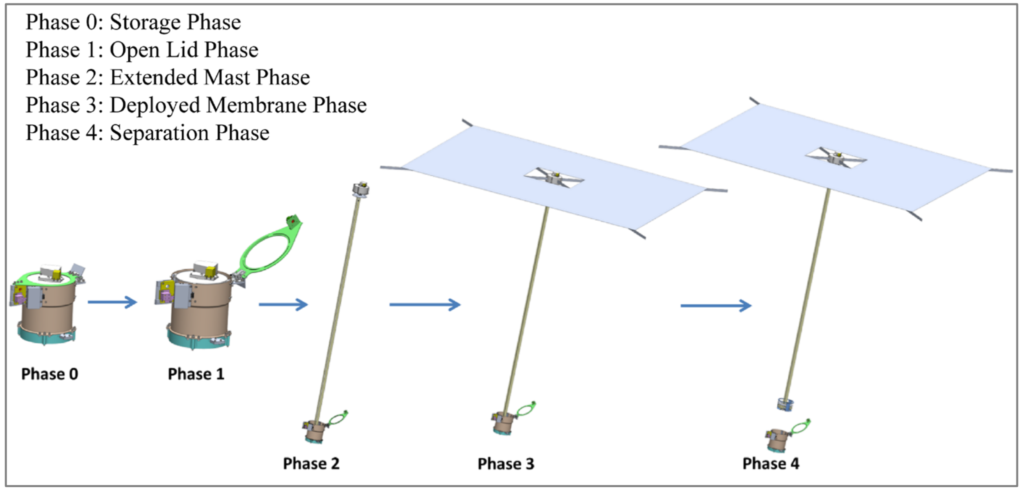
After vibration test

What are the problems?

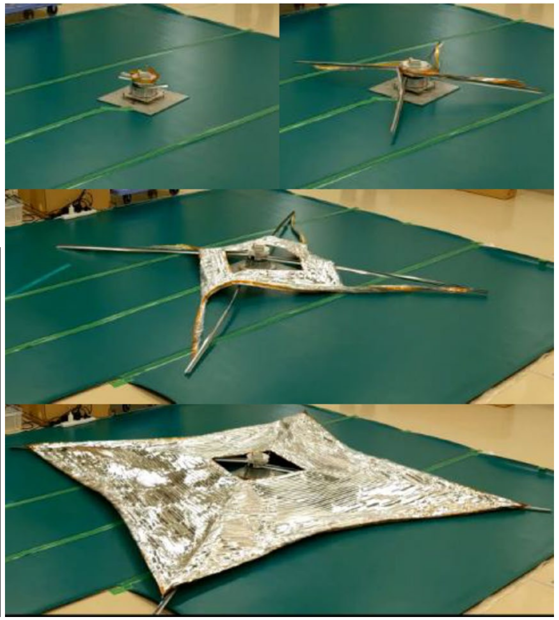
★Prediction of deployment behavior

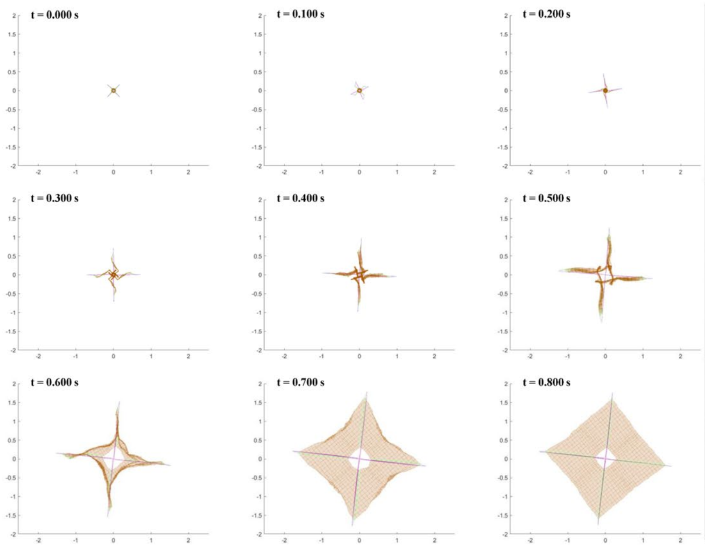
- The numerical technique has been improved, but the numerical simulation of the deployment of membrane structures is still not easy (e.g., self-contact of membrane, parameter identification).

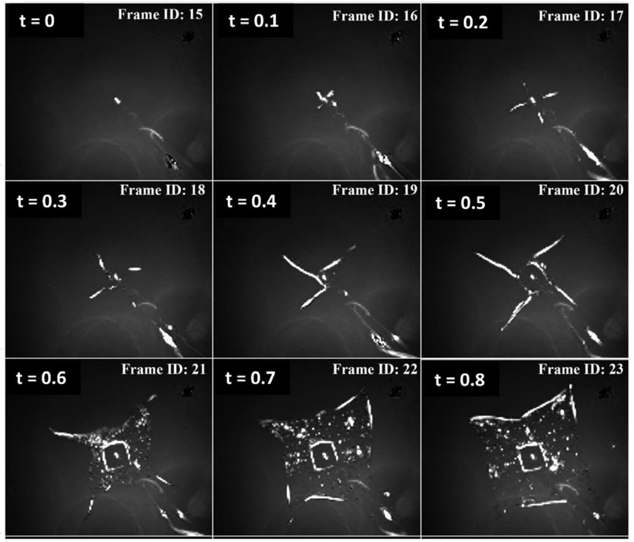
Deorbit mechanism installed on ALE-1 satellite



Dr. Alperen Ahmed (Tohoku U)







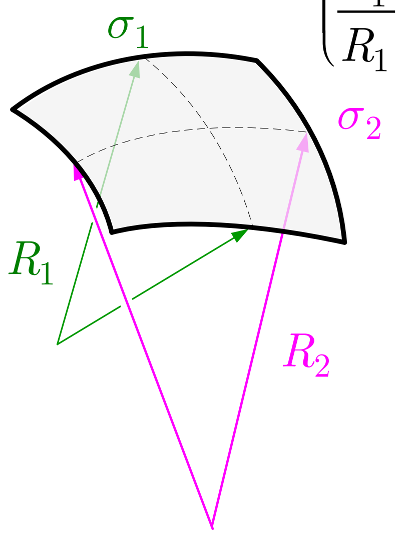
What are the problems?

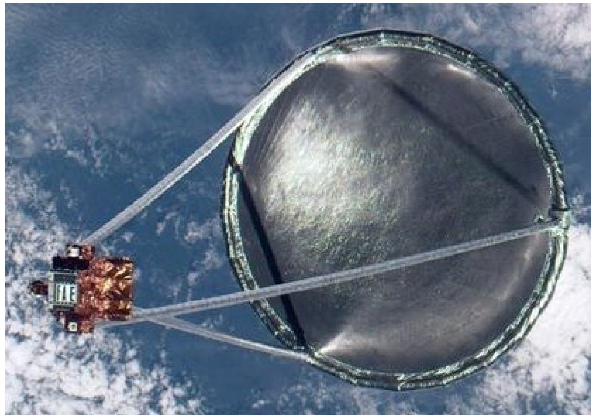
★Stiffness after deployment

- The our-of-plane stiffness of the tensile structure depends on (stress)/(length).
- If the structure is enlarged, the stress should be larger to keep enough out-of-plane stiffness.
- However, if the stress is larger, the margin of safety to the allowable stress becomes smaller, i.e., the strength design becomes difficult.

Inflatable membrane

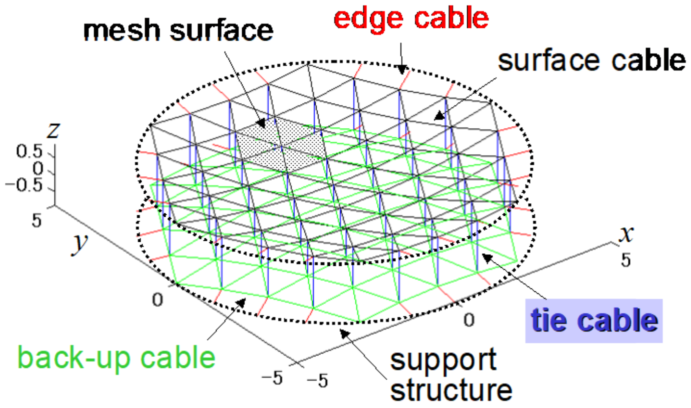
$$\left(\frac{\sigma_1}{R_1}+\frac{\sigma_2}{R_2}\right)h = p$$





Cable

$$\boldsymbol{K} = \frac{EA}{\ell_o}\tilde{\boldsymbol{k}}_m + \frac{\sigma A}{\ell}\tilde{\boldsymbol{k}}_g$$

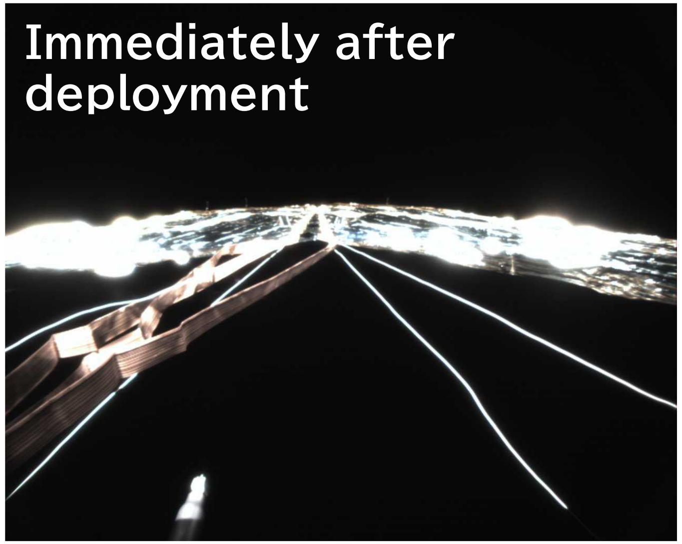


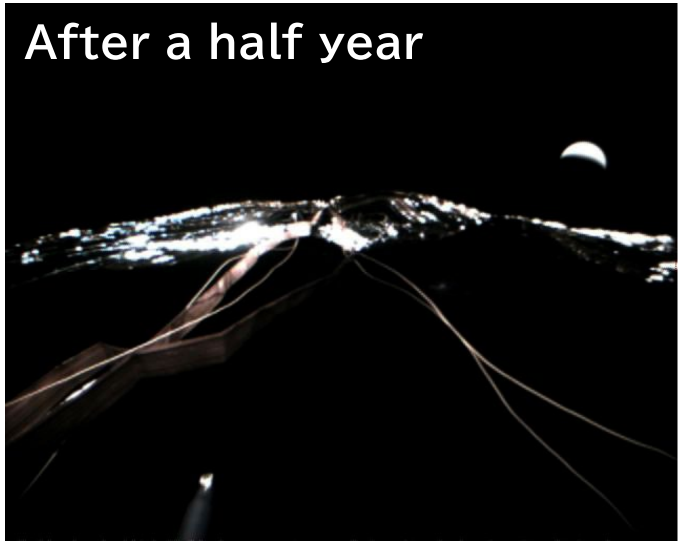
What are the problems?

★Shape accuracy

- The shape of the membrane is sensitive to the dimensional error of each parts, spring-back effect of the fold-line, (quite small) bending stiffness of the membrane, the stiffness of the attached devices such as solar cells.
- In case of IKAROS, asymmetric shape of the sail membrane caused the spin torque of the solar pressure (called "windmill effect"), so that much propellant was consumed for the attitude control.
- That means the solar sail is not propellant-free spacecraft if the sail shape is not controlled.

Shape of sail membrane of IKAROS



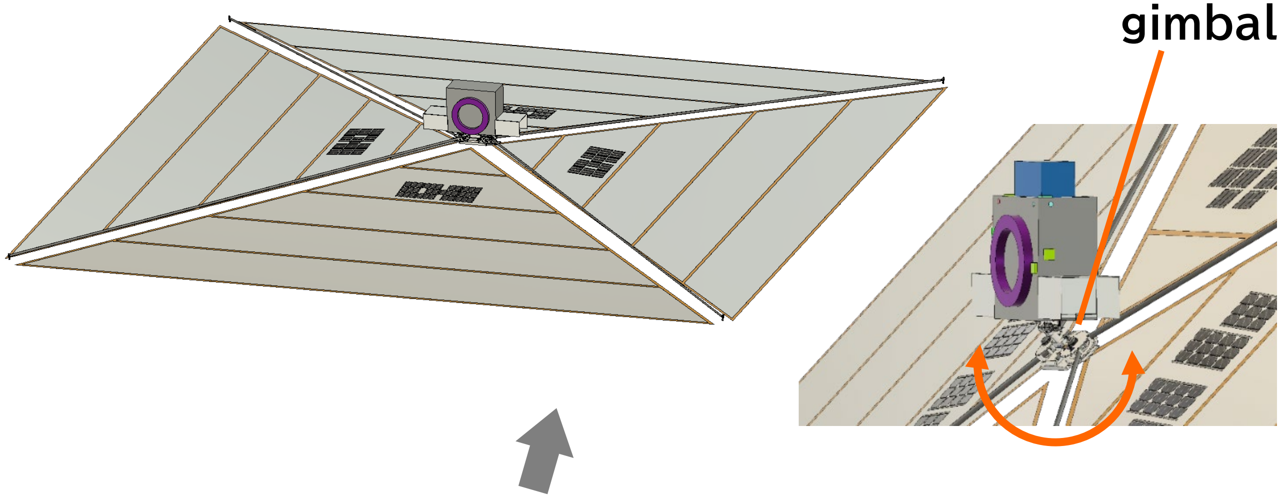


What are the problems?

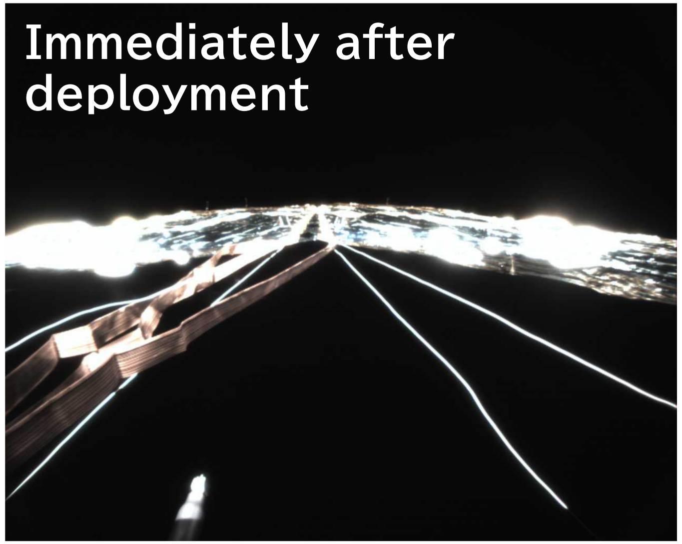
★Shape accuracy

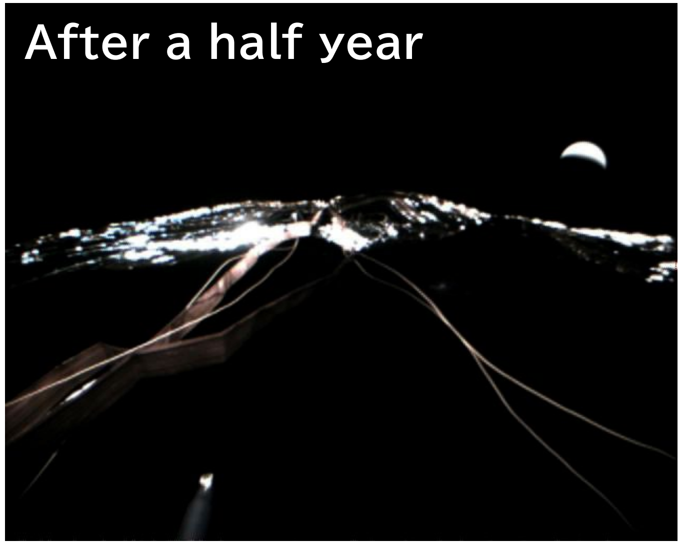
- So, Prof. Chujo has proposed a pyramid-like solar sail that can change the attitude of the sail membrane to the spacecraft body by using a gimbal.
- The requirement of the shape accuracy of the sail structure is quite high(e.g., the equivalent torsional angle should be less than a few degrees).

Pyramid-like solar sail with gimbal



Shape of sail membrane of IKAROS

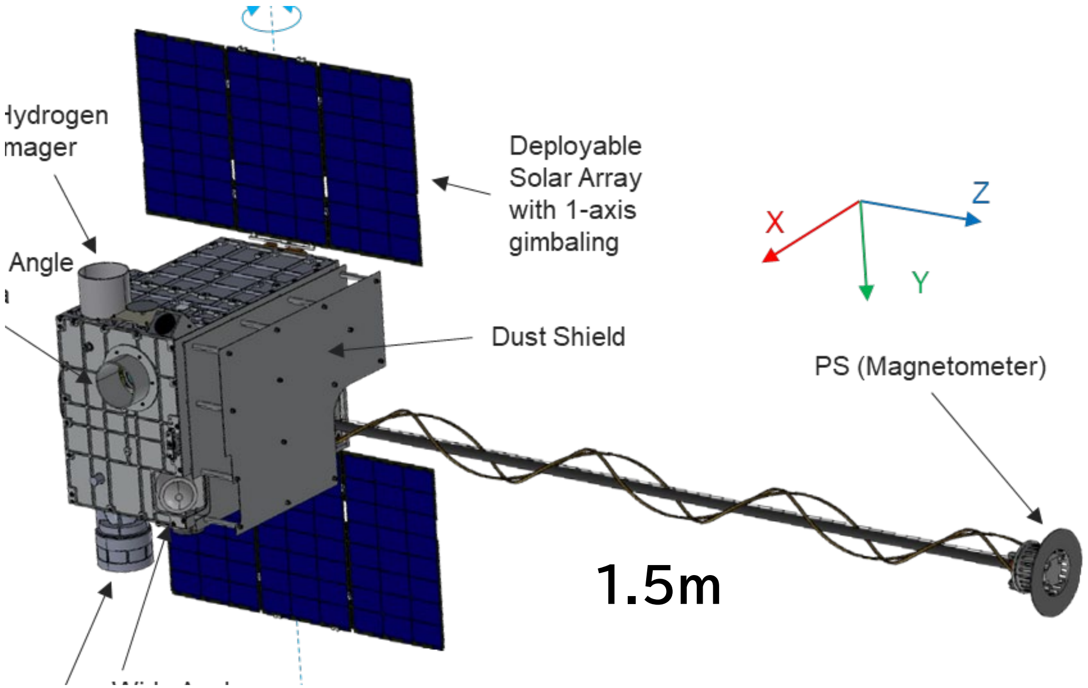




What are the problems?

★Shape accuracy

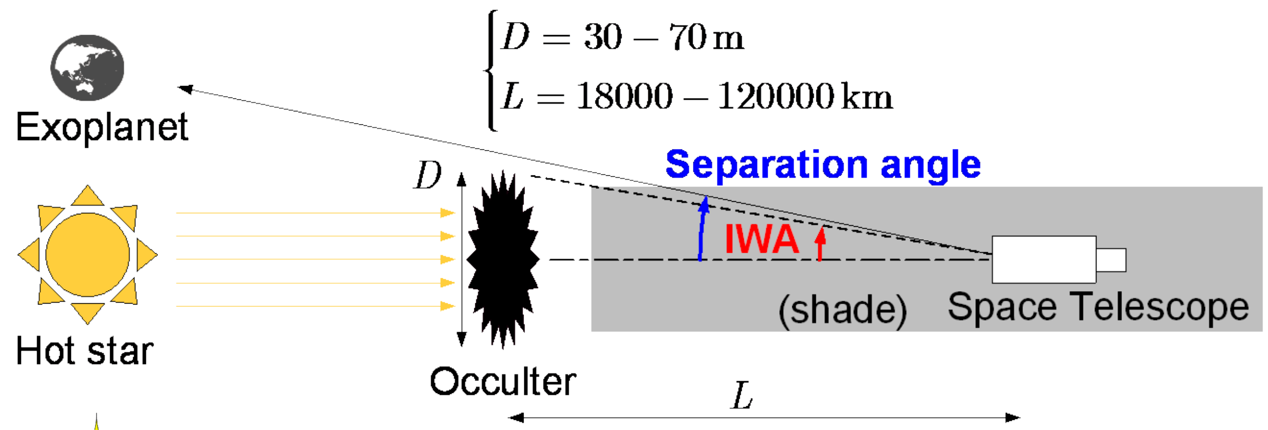
- In case of Comet interceptor, tip attitude error of the extensible boom for the magnetometer must be less than 5 degrees.
- If the boom is rigid, we can satisfy this requirement easily, but if the boom is made of the composite, it is not easy because CFRP has time-dependent behavior such as viscoelasticity.

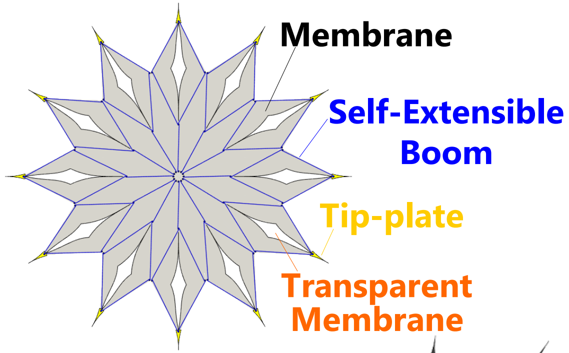


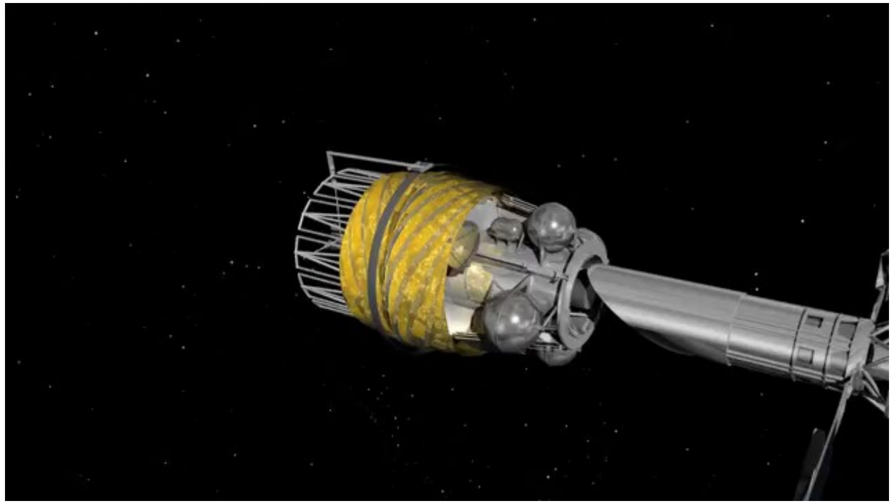
What are the problems?

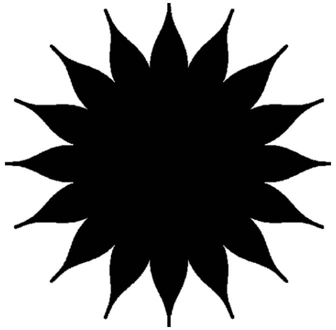
★Shape accuracy

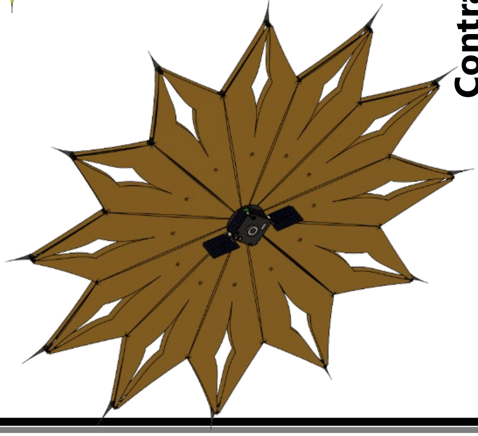
- Some of future missions require large deployable structure with high shape accuracy.
- Starshade enables the direct imaging of exoplanets. It requires about 50m deployable structure with 1 cm accuracy.
- I need the idea to achieve the requirement!

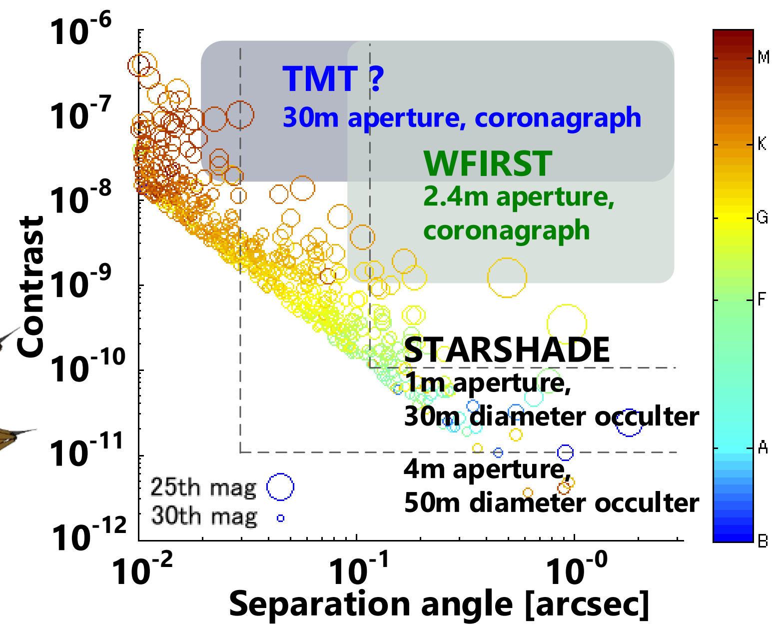












Summary

1. Deployable structure is often required in space exploring mission.
2. Currently, very lightweight deployable planar structure and extensible boom are especially desired.
3. Rolled-up thin-walled composite/metal boom has been researched and is being realized in deep space exploring mission.
4. There are a few difficulties in the development of such highly flexible lightweight large structure.
    a. Verification of the deployment system on the ground (before launch) to guarantee the success of the deployment
    b. Tolerance to launch environment (vibration)
    c. Prediction of deployment behavior
    d. Stiffness after deployment
    e. Shape accuracy