New Challenges for Deep Space Exploration with Micro/Nano Satellites

Prof. Ryu Funase
(Univ. of Tokyo & JAXA/ISAS)

1) 2000~2007: Small sat missions at U. of Tokyo

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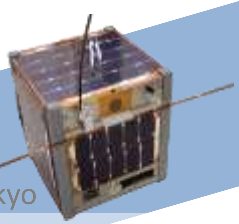
CanSat
(2002)



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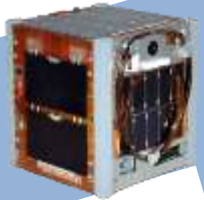
XI-IV (2003): 1kg
World's first CubeSat



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XI-V (2005): 1kg
Tech Demo.

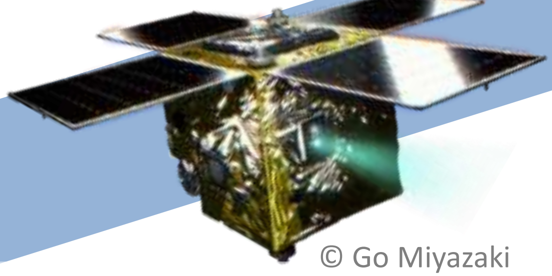
2) 2007～2012: (Not so small) deep space missions at JAXA

Hayabusa (2007-2010)
Asteroid sample return

IKAROS (2007-2010)
World's first interplanetary solar sail

Hayabusa2 (2009-2012)
Asteroid sample return

3) 2012～2019+ Deep space × small sat at U. of Tokyo



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PROCYON(2014): 65kg
World's first deep space micro-sat

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EQUULEUS(2021): 11kg
First CubeSat to explore lunar Lagrange point

General discussion of deep space exploration missions

Example of deep space missions – exploration targets

- **Planets**
  - Mercury, Venus, Mars, Jupiter, Saturn,…
- **Satellites**
  - (Earth's) Moon, Phobos
- **Asteroids**
- **Comets**
- **Interstellar objects**
  - 'Oumuamua, Borisov,…
- Others?

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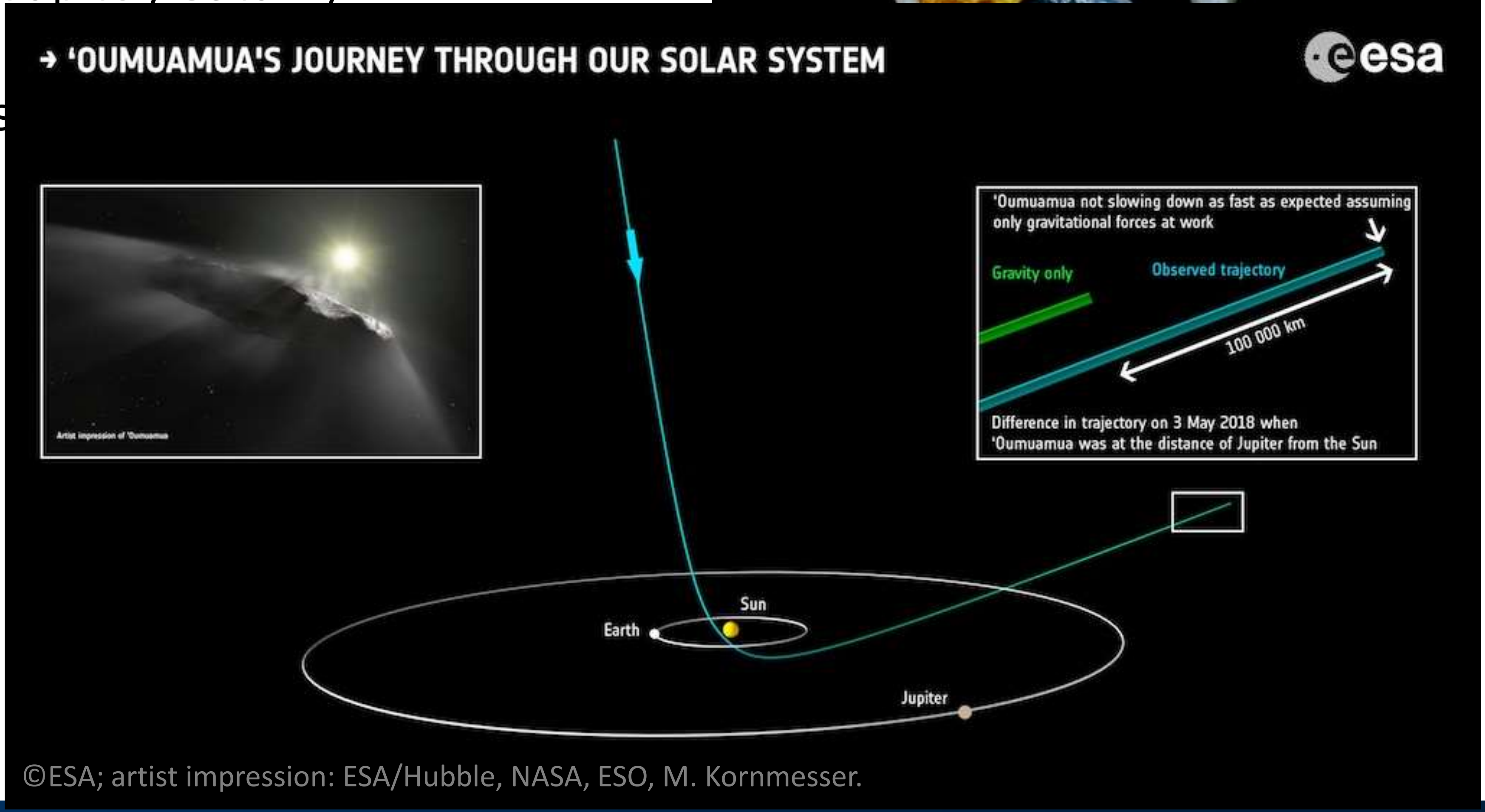

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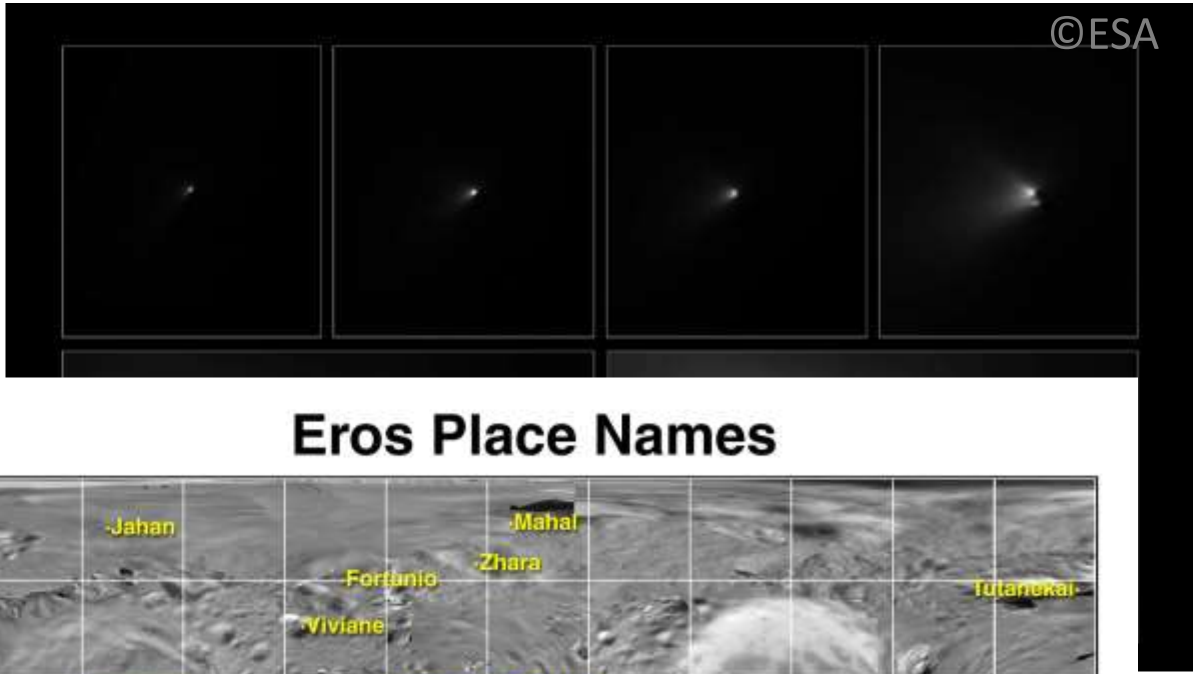
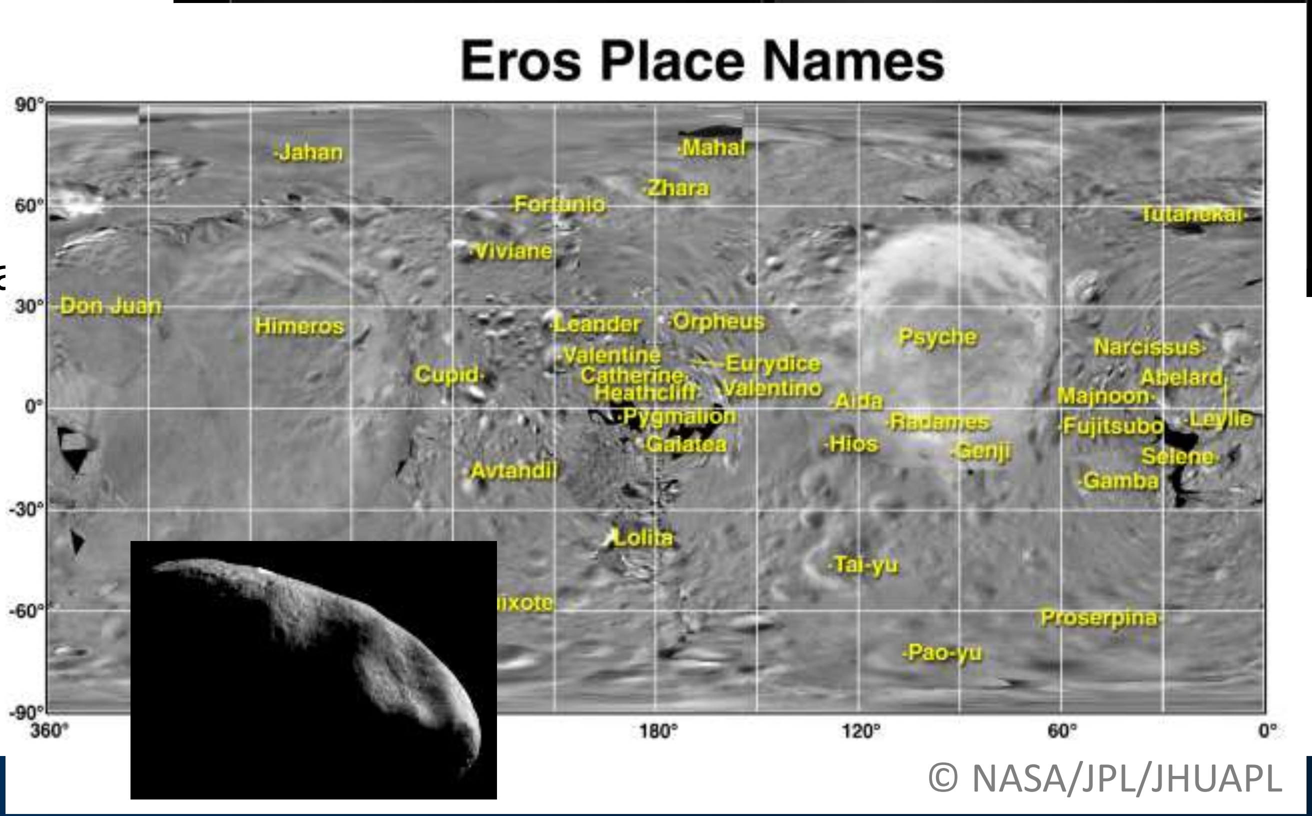
Example of deep space missions – mission styles

- Flyby
  - **Giotto** (ESA, 1985, Halley Comet)
- Rendezvous
  - **NEAR** (NASA, 1996, Asteroid “Eros”)
- Orbiter
  - **Galileo** (NASA, 1989, Jupiter)
- Landing
  - **Mars Pathfinder** (NASA, 1996, Mars)
- Sample return
  - **Hayabusa** (JAXA, 2003, Asteroid “Itoka

High complexity, large delta-V, etc





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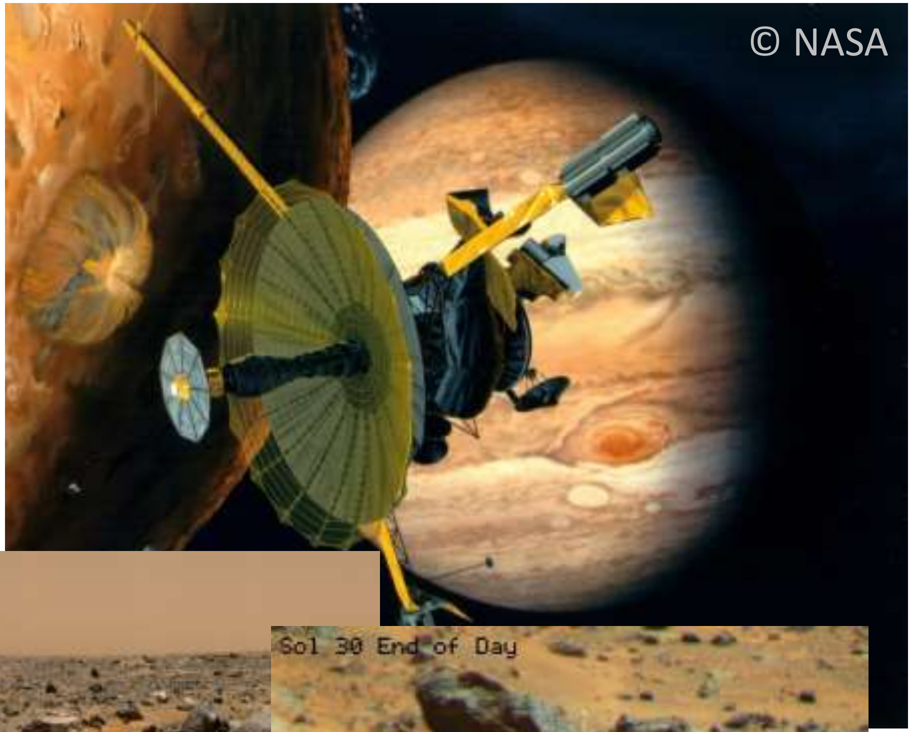

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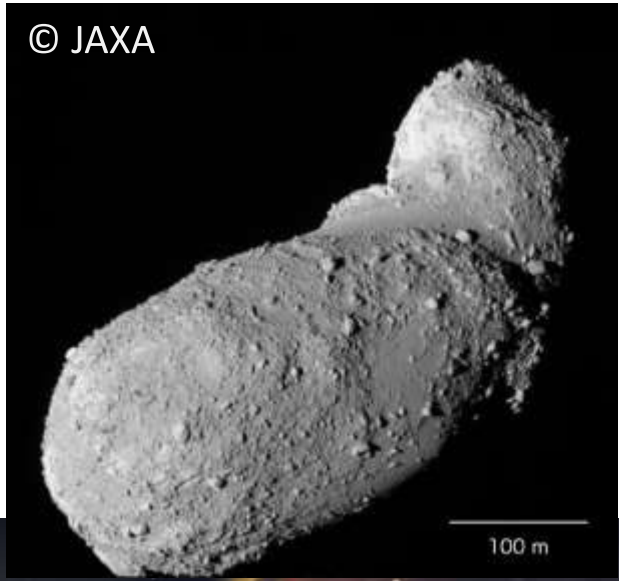

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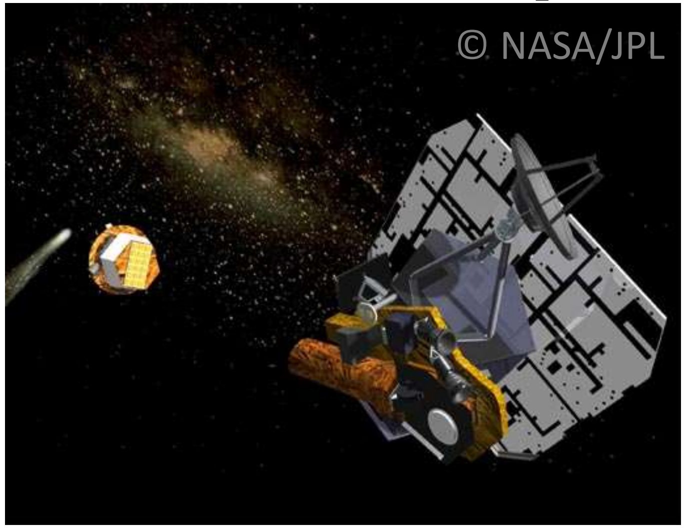
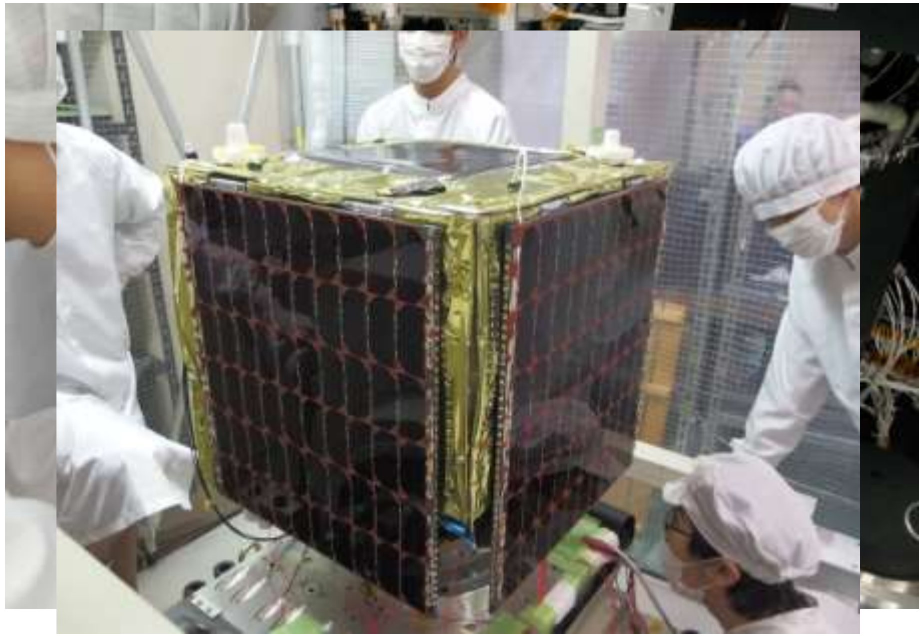


- Others
  - Impactor (**Deep Impact**, **DART/Hera**)
  - Multi-point measurement by multi-S/C (**Comet Interceptor**)

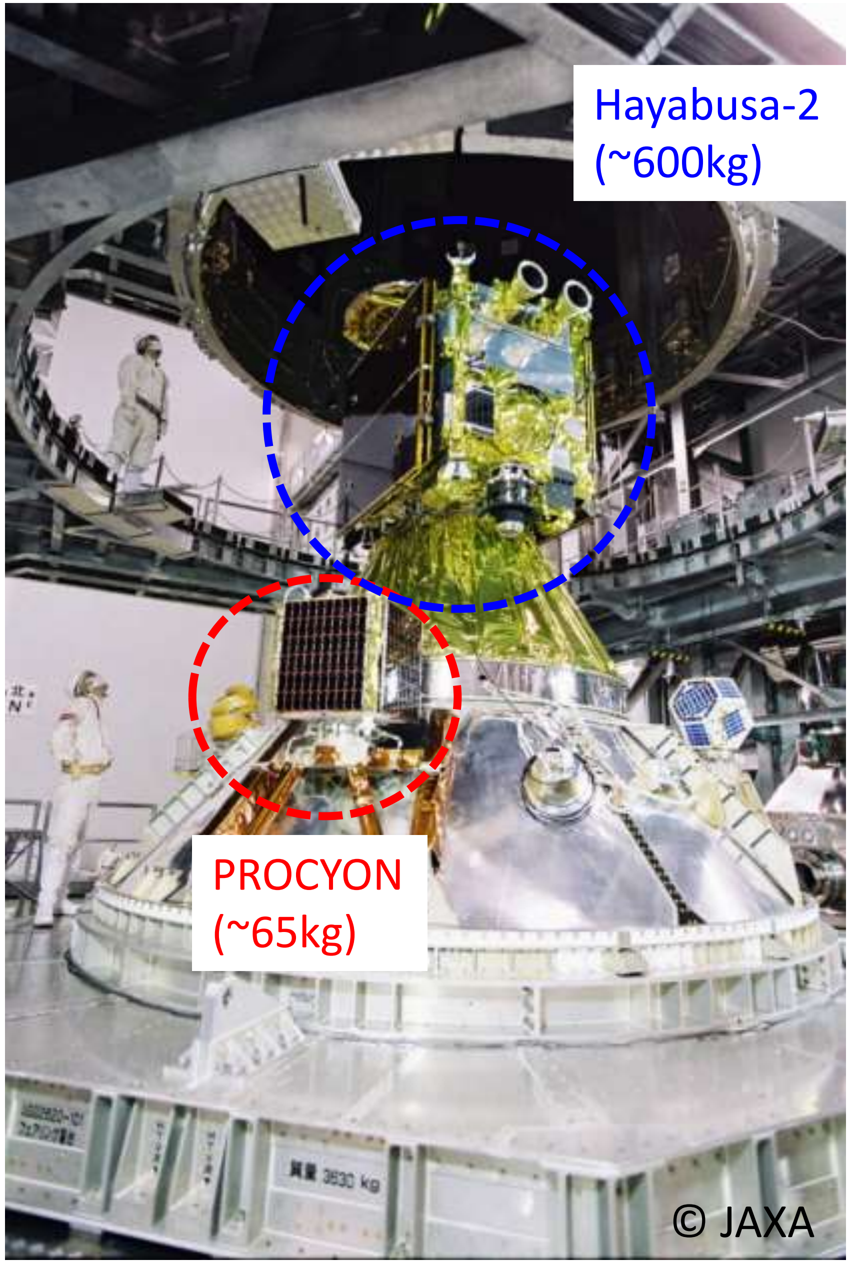
Examples of micro/nano satellites for deep space mission

The first 50kg-class deep space exploration by PROCYON (Univ. of Tokyo + JAXA)



(during integration/testing)

(ion thruster test in a vacuum chamber)



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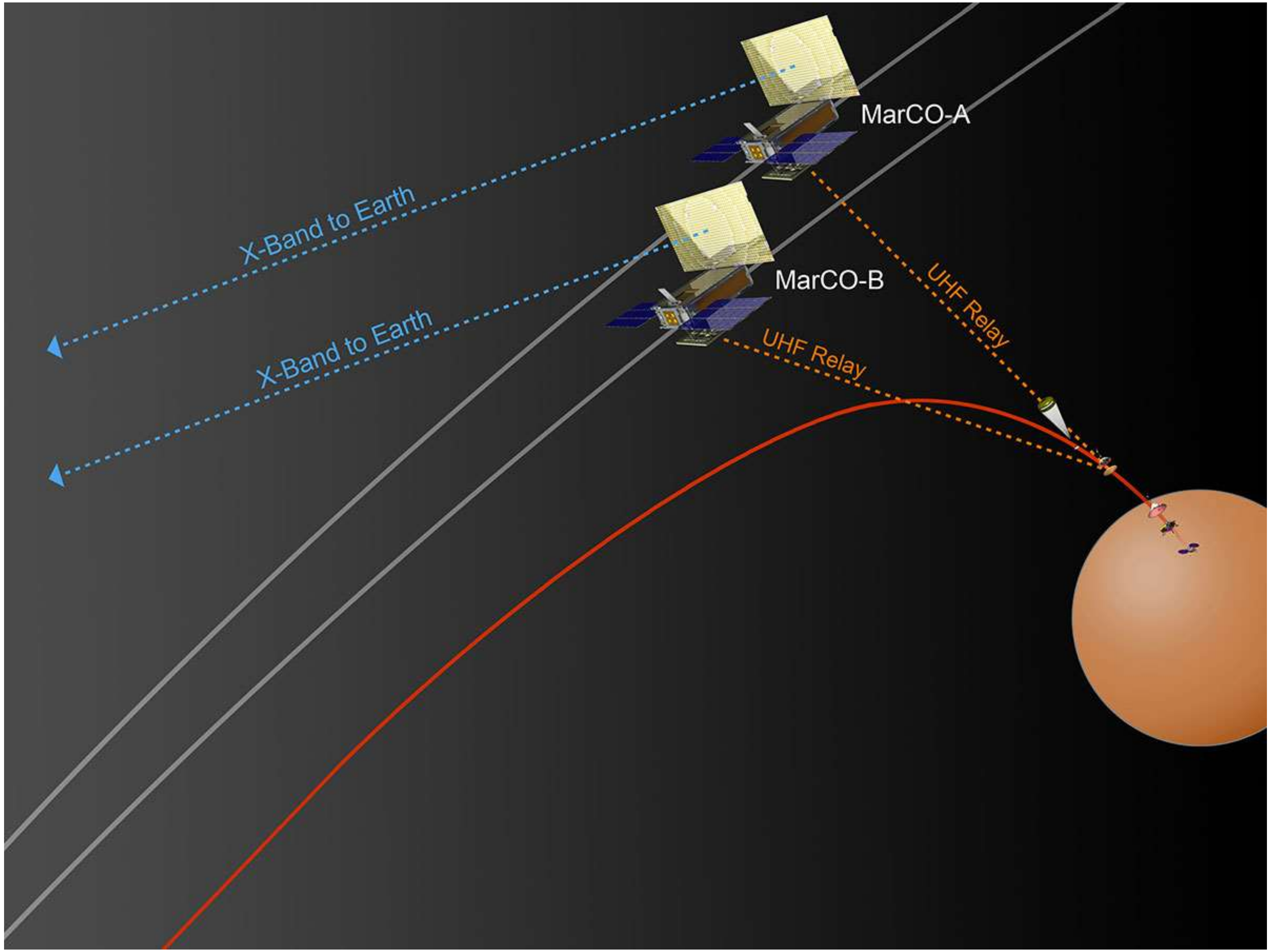
EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft)

6U CubeSat to fly to Lunar Lagrange point onboard SLS Artemis-1 in 2021

Missions

- ✓ Low-energy trajectory control demonstration within Sun—Earth—Moon region
- ✓ Earth's plasmasphere observation
- ✓ Lunar impact flashes observation
- ✓ Characterization of dust in the cis-lunar region

The first deep space CubeSat: MarCO (by NASA/JPL, 2018)



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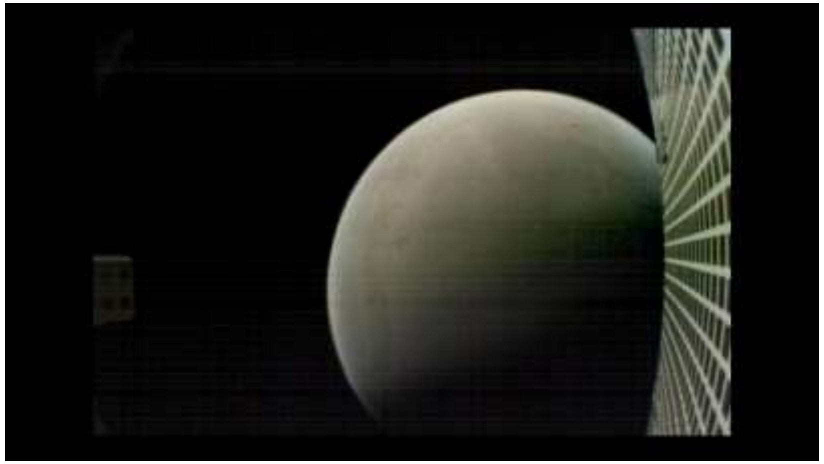
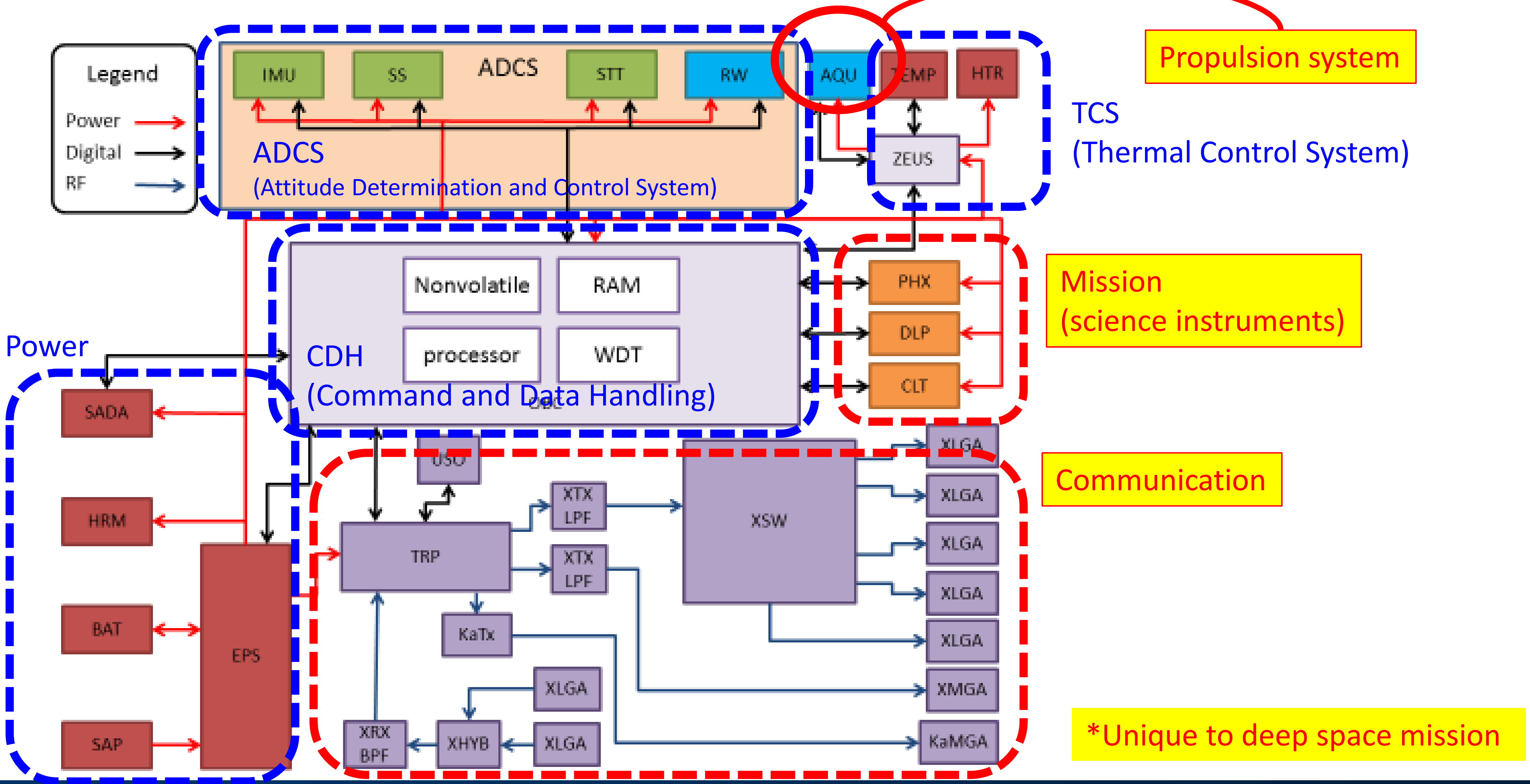


Conceptual design process for deep space missions

System block diagram of deep space probes



Overview of the design flow for deep space missions

1. Target selection
2. Trajectory design & launch mass calculation
3. Mission-subsystem design
4. Communication-subsystem design
5. ADCS design
6. Power-subsystem design
7. Structure &thermal design

1. Target selection

- Choose the target of the mission (i.e. identify what planetary body you will explore in your mission)
  - Planets, Satellites, Asteroids, Comets, Interstellar Objects, etc

- Clarify the rationale of exploring the target (i.e. why you explore the target and what knowledge you will acquire from your mission)
  - e.g. Study the origin and evolution of the solar system by exploring the C-type asteroid “Ryugu”

This step is the most important because how much personal interest and motivation you have in your mission will determine how enthusiastic you are in the subsequent hard design works and finally determine the quality of your work.

2. Trajectory design & launch mass calculation

1. **Design interplanetary trajectory** from the Earth to the target by solving “**Lambert problem**”.
    i. Specify when the S/C departures Earth and arrives at the target.
    ii. Calculate the position of the Earth and the target in the Sun-centered inertial coordinate. (You can obtain the ephemeris for celestial bodies from various free databases such as “JPL HORIZONS”.)
    iii. Solve lambert problem under the above conditions, then you can obtain Earth departure relative velocity and target arrival relative velocity. (You will find free Lambert problem solver in the web such as “pykep”)
    iv. Search the optimal departure and arrival timing to minimize the relative velocities.

2. You should consider to **use “gravity assist”** if you want to reduce the necessary delta-V.
    – see Jon A. Sims, et al., “V∞ Leveraging for Interplanetary Missions: Multiple Revolution Orbit Techniques”, JGCD, Vol.20, No.3, pp.409-415, 1997

3. **Calculate the launchable mass** corresponding to the required Earth departure C3 by using the “C3 vs. Launch Weight” chart.

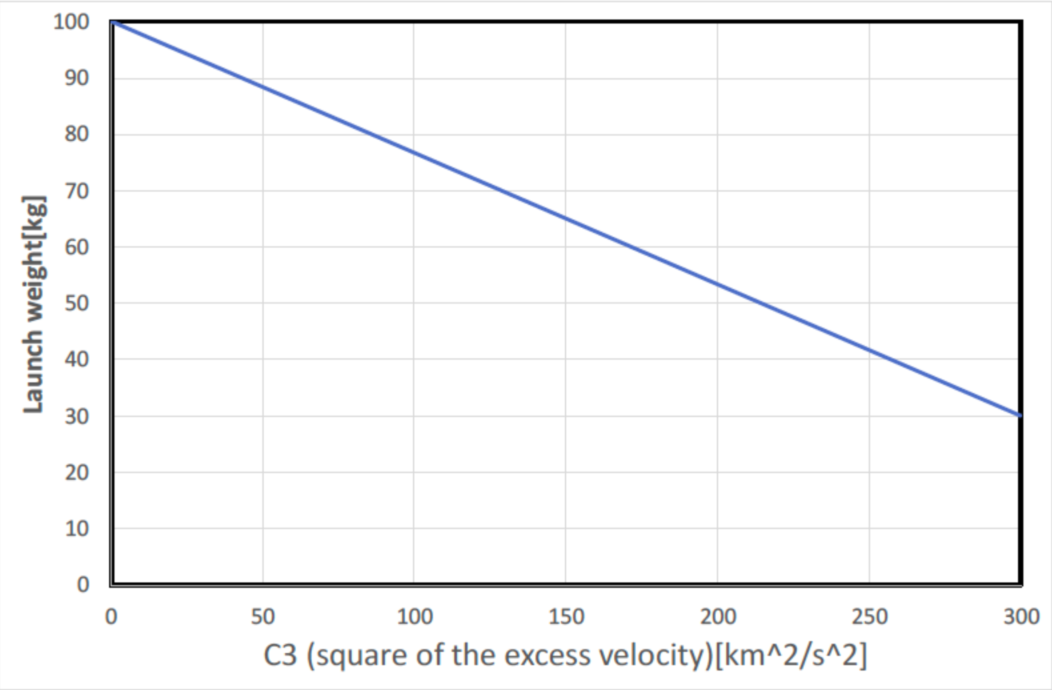


Figure 1 C3 vs. Launch Weight (TBD)

(from http://www.spacemic.net/pdf/mic7/MIC7_constraints.pdf)

2. Trajectory design & launch mass calculation (cont'd)

4. Calculate the necessary **delta-V to insert the S/C into its mission orbit**.
   – For rendezvous missions, you need to decelerate the S/C (i.e. need delta-V) to completely cancel out the relative velocity to the target at arrival.
   – For orbiter missions, you need to decelerate at a periapsis of the incoming hyperbolic trajectory around the target body, which will require relatively large delta-V.
   – For flyby missions (and impactor missions), you will need only small delta-V (e.g. < 100 m/s) to adjust the relative trajectory to the target

5. Calculate the **final dry mass** of the S/C at an arrival at the mission orbit
   – Use the "Tsiolkovsky equation":

$$\Delta V = g I_{sp} \ln \frac{m_i}{m_f}, \text{or } m_f = m_i \exp \frac{-\Delta V}{g I_{sp}}$$

   – Note that the result strongly depends on the **selection of propulsion system**; type (chemical/electric/others) and performance of the propulsion system (i.e. specific impulse I_{sp})

6. Go back to step 1 (target selection) if you are not satisfied with the results at this moment. (e.g. the resultant residual mass becomes too small, and the intended mission will not be achieved with this small mass)

3. Mission-subsystem design

- Consider **what physical quantities** need to be observed and **what instruments** are required to do so, in order to carry out the intended mission.

- A completely new conceptual design of the instrument is welcome, but it may be difficult to do so. You may refer to the onboard instruments of past missions that perform similar observations.

- The output of this step will be:
  - **Size, mass, power** of the instruments
  - FoV (field of view) of the instruments
  - **Data volume and data rate** requirement (i.e. how much data is generated by the instrument and how fast (how much bit rate) the mission data should be downlinked to the Earth)
  - **Attitude control, determination** accuracy and **attitude stability** requirement
  - etc

4. Communication-subsystem design

- Divide the entire mission period into several phases and calculate the **communication data rate requirement** for each phase.
  - For example, you need to consider the followings:
    - HK (House Keeping) telemetry which contains critial information to represent the health status of the spacecraft should always be downlinked at a certain frequency (e.g. every 10 minutes).
      - For PROCYON, the size of HK telemetry was ~500byte/packet, and the minimum requirement for HK telemetry downlink frequency was 30 sec/packet.
    - How much HK data is stored during the invisible time?
      - Part of this data volume needs to be downlinked during the next visible time to ensure that the spacecraft health status was normal during the invisible time.
    - In addition to HK telemetry, large amount of mission data (e.g. observation data, etc) is generated, and it should be downlinked within the entire mission period.

4. Communication-subsystem design (cont'd)

- Design the communication system to satisfy the data rate requirement. **The key design parameters** are as follows:
  - **RF output power** (W) (which corresponds to the size, weight, power consumption, and heat generation of the power amplifier)
  - **Uplink and downlink antenna gain** (dBi) (which corresponds to the size and weight of the antenna and the antenna beam width)

- **Useful references**
  - An example of deep space communication system design:
    Kobayashi, Y., Tomiki, A., et al., "Low-cost and ultimately-downsized X-band deep space telecommunication system for PROCYON mission", IEEE Aerospace Conference, MT, USA, 2016. DOI: 10.1109/AERO.2016.7500745
    https://ieeexplore.ieee.org/document/7500745
  - Information about NASA Deep Space Network (DSN):
    https://deepspace.jpl.nasa.gov/files/820-100-F1.pdf

5. ADCS (Attitude Determination and Control System) design

- Most of the mission will use (require) 3-axis stabilization for attitude control.

- In deep space, attitude control and unloading of angular momentum using the earth's magnetic field are basically not possible, so an external torque generation source other than the magnetic torquer (typically, a propulsion system) is required in order to (at least) manage the total angular momentum of the spacecraft.

- Similarly, attitude determination using an earth sensor or a magnetic sensor is impossible.

- Typical configuration of 3-axis ADCS for deep space mission:
  - Sensor: sun sensor, star tracker, Gyro
  - Actuator: RW (Reaction Wheel), RCS (Reaction Control System, i.e. propulsion system)

5. ADCS design (cont'd)

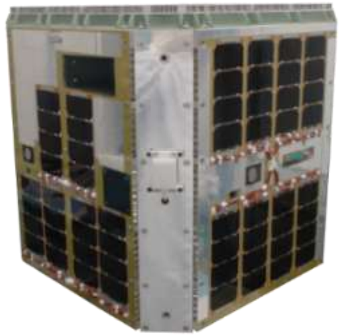
- If mission-specific requirement for ADCS (**Attitude control, determination** accuracy and **attitude stability** requirement) is within the performance of the existing attitude control system for nano/micro-satellite, you will not have to consider (design) how to achieve such high accuracy. You can assume **existing attitude control systems**.
  - For CubeSats, an integrated ADCS unit and a miniature cold-gas propulsion system is normally used.
  - For larger micro-satellites (~50-100kg), appropriate RWs should be selected considering the moment of inertia of the spacecraft.

- **The major attitude disturbance source in deep space is SRP** (solar radiation pressure). Note that when using a large solar array paddle, angular momentum tends to accumulate due to disturbance. High speed of angular momentum accumulation will lead to large propellant usage for momentum desaturation, which threatens the mass budget of the spacecraft.
- The maximum angular momentum capacity of the RWs should be large enough in order to keep the frequency of the desaturation (or unloading) operation low.

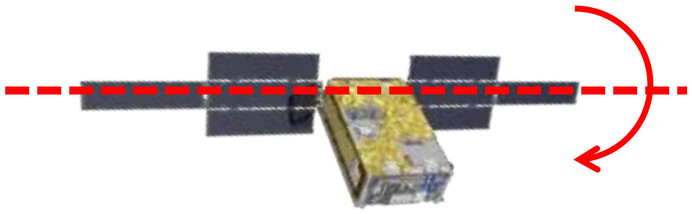
- **Useful references**
  - **EQUULEUS ADCS design**
    Nomura, S., et al., "Initial Design of EQUULEUS Attitude Determination and Control System: How to Design an ADCS with High Reliability for a Deep Space CubeSat", 31st International Symposium on Space Technology and Science, Matsuyama, Japan, June 2017, https://archive.ists.or.jp/upload_pdf/2017-f-046.pdf
  - **PROCYON ADCS design**
    Ikari, S., et al., "Attitude Determination and Control System for the Micro Spacecraft PROCYON", Transactions of the Japan Society for Aeronautical and Space Sciences, Vol.60, No.3, pp.181-191, 2017, https://doi.org/10.2322/tjsass.60.181

6. Power-subsystem design

- **Body-mounted solar cell or solar array paddle?**
  - Subsequent spacecraft design task will become much easier if the **body-mounted solar cells** can supply enough power for the mission. So, it will be a good idea to examine whether the design is feasible with body-mounted solar cells. However, note that there will be some difficulties (or lack of design flexibility) in the thermal design of the spacecraft if its outer surface is covered with solar cells.
  - When **deployable solar array paddles** are necessary, the spacecraft design's complexity becomes very large, and you will need to conduct a complicated equipment layout design that meets various constraints in the operation of the spacecraft.
  - Example of the operational constraints related to the equipment layout design:
    - Mission instrument should point to the target in the observation mode.
    - The antenna of the spacecraft should point to the Earth during the observation mode in order to keep contact with the spacecraft during observation. (Note that you don't necessarily have to operate that way for every mission.)
    - The solar array paddle should point to the solar direction in order to supply enough power for the high-power-consumption mission instrument while conducting the observation.
  - In order to satisfy all operational constraints as described above, using a solar array paddle with gimbaling mechanism will be a solution in some cases.



Micro-satellite with body-mounted solar cells



6U CubeSat with deployable solar array paddles with gimbaling mechanism

6. Power-subsystem design (cont'd)

- **Battery**
  - If the spacecraft will experience eclipse during the mission (from launch to end of operation), it should be equipped with a battery of adequate capacity as a power source to provide power during that period.
  - Even if not, batteries are necessary to provide power during the period immediately after the release from the launch vehicle (before the solar array paddle deployment), and to temporarily provide power in case of an attitude control anomaly.
  - For missions that experience repeated eclipses, the depth of discharge (DoD) needs to be kept at an appropriately small value to avoid battery degradation, which requires a larger battery capacity.

- **Power control unit (PCU)**
  - You need to select an appropriate component that corresponds to the scale of the spacecraft power generation capability.

6. Power-subsystem design (cont'd)

- **Power budget analysis & sizing of solar array paddle**
  - From the examinations so far, it should be clear that the operation will be carried out in several "power modes" (combinations of devices to be turned on).
  - Identify in which power mode and in which attitude (especially the solar direction) which type of operation is the most demanding in terms of power balance (i.e. power consumption vs. power generation).
  - Then, calculate the necessary area for solar cells so that the power balance is established under the worst-case condition.

- **Useful reference**
  - **EQUULEUS power subsystem design**
    Murata, Y., et al., "Power Management of Lunar CubeSat Mission EQUULEUS under Uncertainties of Power Generation and Consumption", 2019-f-34, International Symposium on Space Technology and Science, Fukui, Japan, 2019
    https://archive.ists.or.jp/upload_pdf/2019-f-34.pdf

7. Structure and thermal design

- **Structure design**
  - At this stage, you should have a list of the size, weight, and power of your onboard components. Based on this, estimate the mass required for the structure of the spacecraft. In general, the mass of the structure is conservatively about 40% of the total onboard components mass including propellant.
    - e.g.) 39% for PROCYON (50kg-class), 30% for EQUULEUS (6U CubeSat)
  - It is also necessary to consider the layout of the components and to estimate the size of the spacecraft.
- **Thermal design**
  - For the thermal analysis and design, please refer to the general satellite design method.
  - What is peculiar to deep space missions, especially in missions with little or no eclipse, is that it is necessary to satisfy the allowable temperature range of each component in thermal equilibrium state, not in transient state in repeated sunshine and eclipse.
- **Useful reference**
  - EQUULEUS thermal design:

    - Shibukawa, T., et al., ”Implementation and Verification of the Tightly-Coupled Thermal Design of the 6U Deep Space CubeSat EQUULEUS”, 2019-i-10, International Symposium on Space Technology and Science, Fukui, Japan, 2019
      https://archive.ists.or.jp/upload_pdf/2019-i-10.pdf
    - Matsushita, S., et al., “Thermal Design and Validation for a 6U Deep Space CubeSat EQUULEUS under Constraints Tightly Coupled with Orbital Design and Water Propulsion System”, ICES-2019-193, 49th International Conference on Environmental Systems, Boston, Massachusetts, USA, 2019
      https://ttu-ir.tdl.org/handle/2346/84425

Overview of the design flow for deep space missions

1. Target selection
2. Trajectory design & launch mass calculation
3. Mission-subsystem design
4. Communication-subsystem design
5. ADCS design
6. Power-subsystem design
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Reality:
lots of “iterations”

Summary

- In this lecture, I talked about how to think about deep space missions and how to design a spacecraft, referring to examples of actual exploration missions using micro/nano-satellites.

- Deep space missions are not completely different from Earth-orbiting missions, and many of the design methods of Earth-orbiting missions can be followed in the deep space mission their design. However, deep space missions have their own characteristics and difficulties, and I hope this lecture has helped you to understand them.

- **The following topics are specific to deep space missions**, so I hope you will deepen your understanding by attending the other relevant lectures.
  - Trajectory design
  - Mission instruments and operation
  - Propulsion system
  - Communication system

References

- **PROCYON**
  - **[Overview]** Funase, R., et al., "One-year Deep Space Flight Result of the World's First Full-scale 50kg-class Deep Space Probe PROCYON and Its Future Perspective", SSSC16-III-05, 30th Annual AIAA/USU Conference on Small Satellite, Utah, USA, 2016, https://digitalcommons.usu.edu/smallsat/2016/TS3YearInReview/4/
  - **[Communication]** Kobayashi, Y., Tomiki, A., et al., "Low-cost and ultimately-downsized X-band deep space telecommunication system for PROCYON mission", IEEE Aerospace Conference, MT, USA, 2016. DOI: 10.1109/AERO.2016.7500745, https://ieeexplore.ieee.org/document/7500745
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  - **[ADCS]** Nomura, S., et al., "Initial Design of EQUULEUS Attitude Determination and Control System: How to Design an ADCS with High Reliability for a Deep Space CubeSat", 31st International Symposium on Space Technology and Science, Matsuyama, Japan, June 2017, https://archive.ists.or.jp/upload_pdf/2017-f-046.pdf
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- **Others**
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