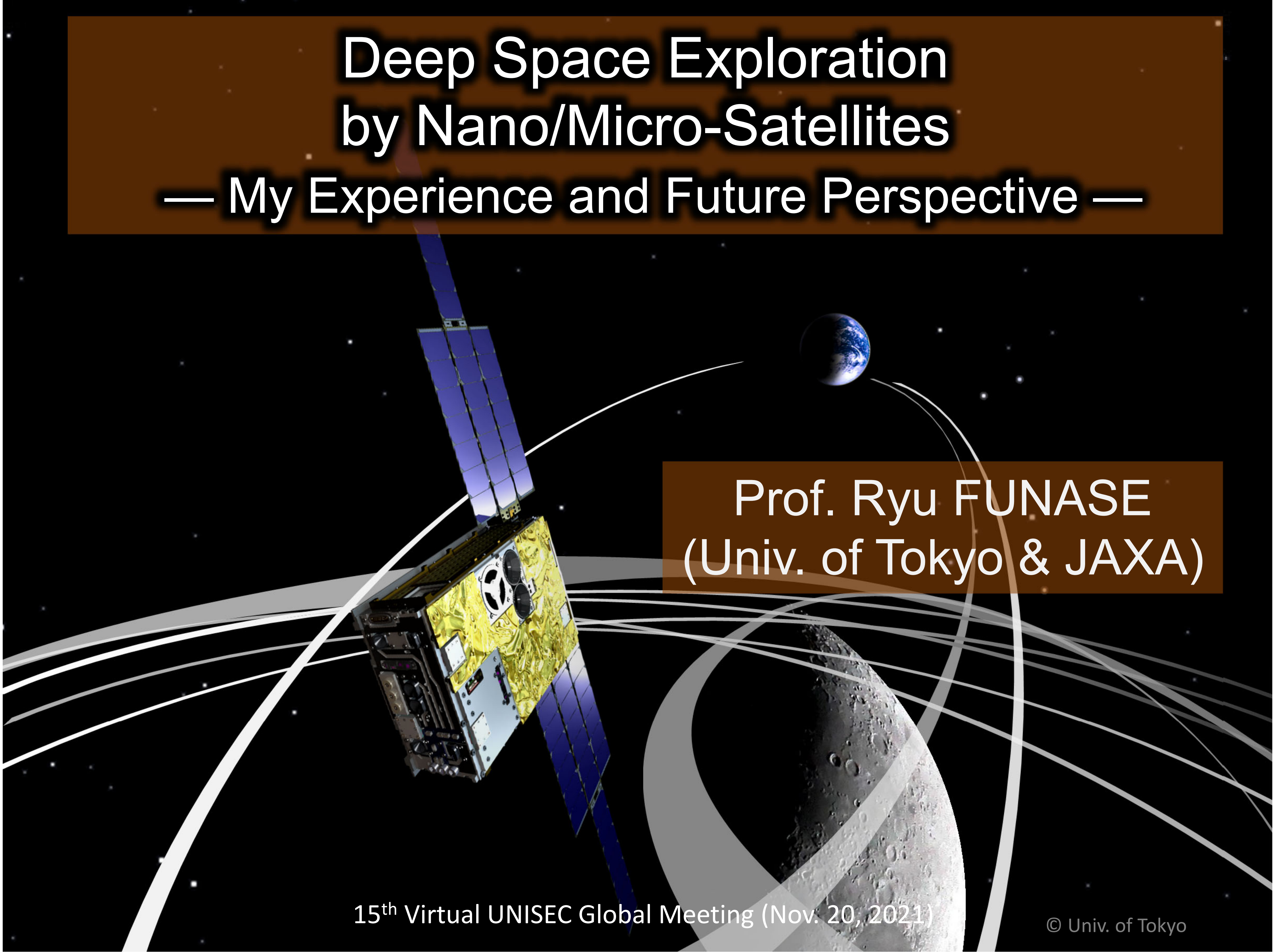
Deep Space Exploration by Nano/Micro-Satellites

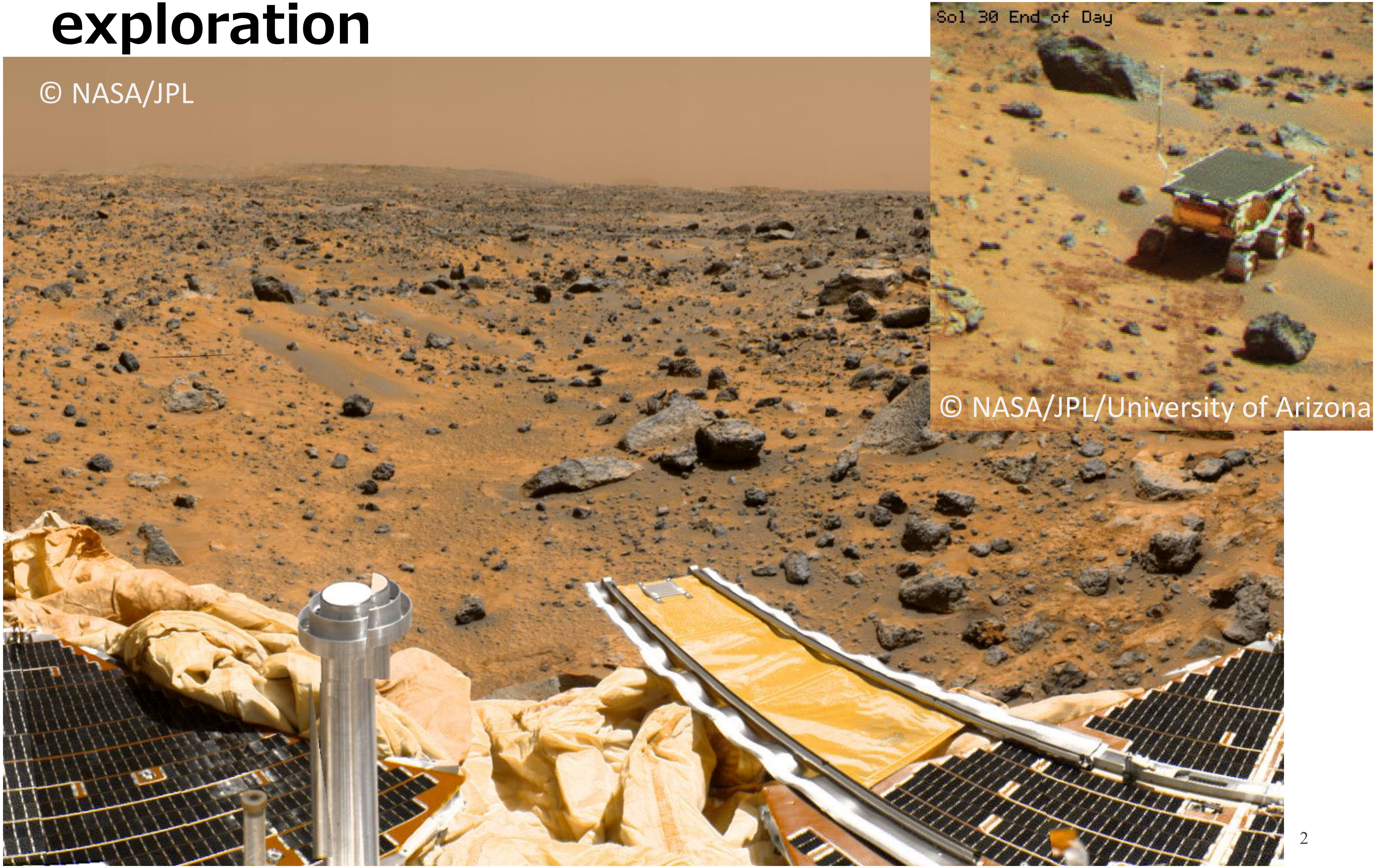
— My Experience and Future Perspective —

Prof. Ryu FUNASE
(Univ. of Tokyo & JAXA)



15th Virtual UNISEC Global Meeting (Nov. 20, 2021)

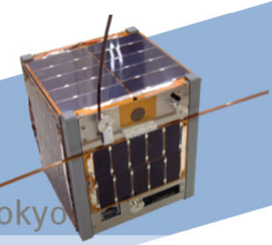
What motivated me to pursue deep space exploration



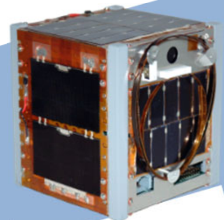
My small satellite experiences at Univ. of Tokyo and JAXA

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

CanSat
(2002)



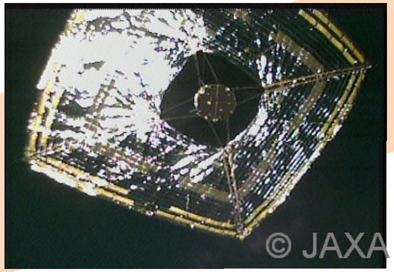
XI-IV (2003): 1kg
World's first CubeSat



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

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

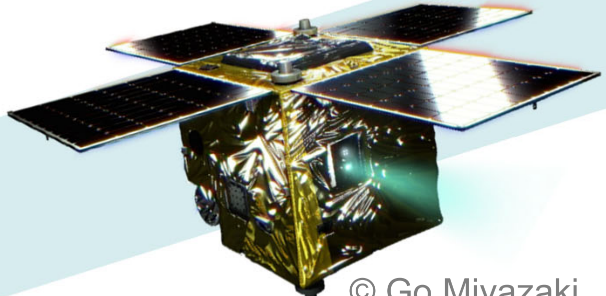
Hayabusa (2007-2010)
Asteroid sample return



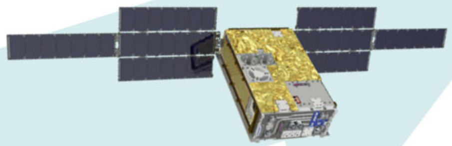
IKAROS (2007-2010)
World's first interplanetary solar sail

Hayabusa2 (2009-2012)
Asteroid sample return

3) 2012~: Deep space × small sat at U. of Tokyo & JAXA



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



EQUULEUS(2022): 11kg
First CubeSat to explore lunar Lagrange point

The First Interplanetary Full-scale Micro-Satellite

PROCYON (2014)

Developer

Univ. of Tokyo + JAXA

Development time

14 months

Development budget

< 5 M$

Launch date

Dec. 04, 2014 (with Hayabusa2)

Mission

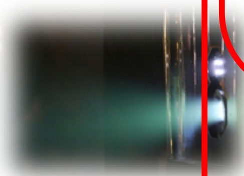
Deep space bus demonstration + science obs. + asteroid flyby

A lot of novel technology demonstrations

Miniature prop. Sys.

Thrusters (RCS)

Manufacturer: The University of Tokyo
Thrust: 22 mN
Specific impulse: 24.5 s
Propellant: Xenon



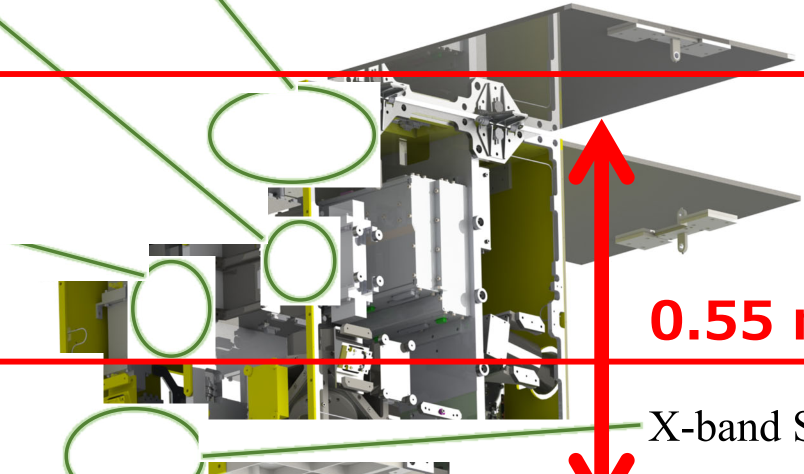
Ion Thruste

Manufacturer: The Univers
Thrust: 300 μN
Specific impulse: 1000 s
Propellant: Xenon

Novel orbit determination method

DDOR Tone Generator

Manufacturer: Digital Signal Techn
Max. output power: +9 dBm (each t
Max. tone width: 86 MHz
Max. sweep width: 7.9 MHz
Sweep time: 2 to 40 min
Alan variance: < 1×10^{-1} (1-100 s),
< 1×10^{-9} (1000 s) (



S/C size: 55cm
S/C mass: 65kg

0.55 m

X-band Transp

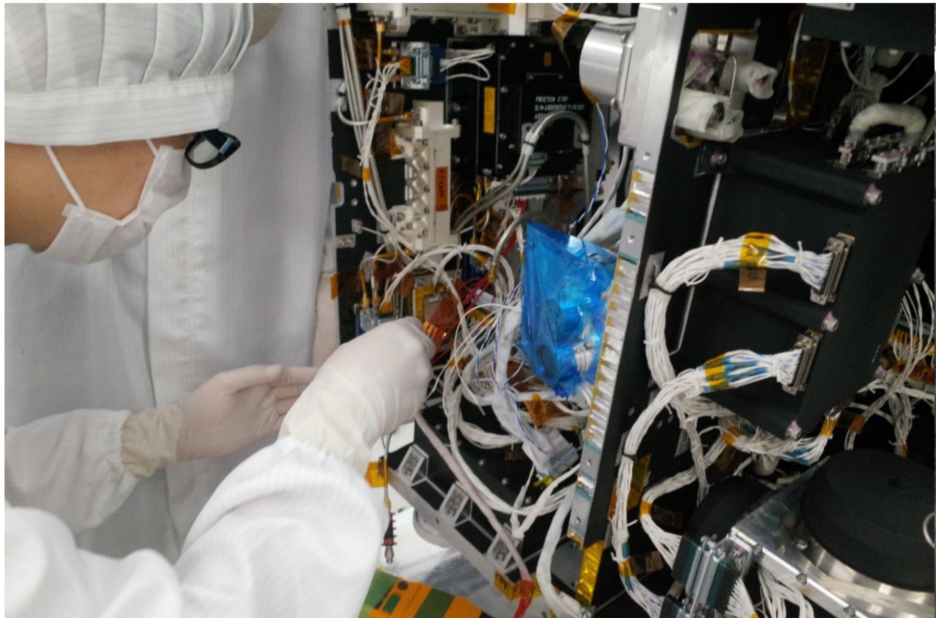
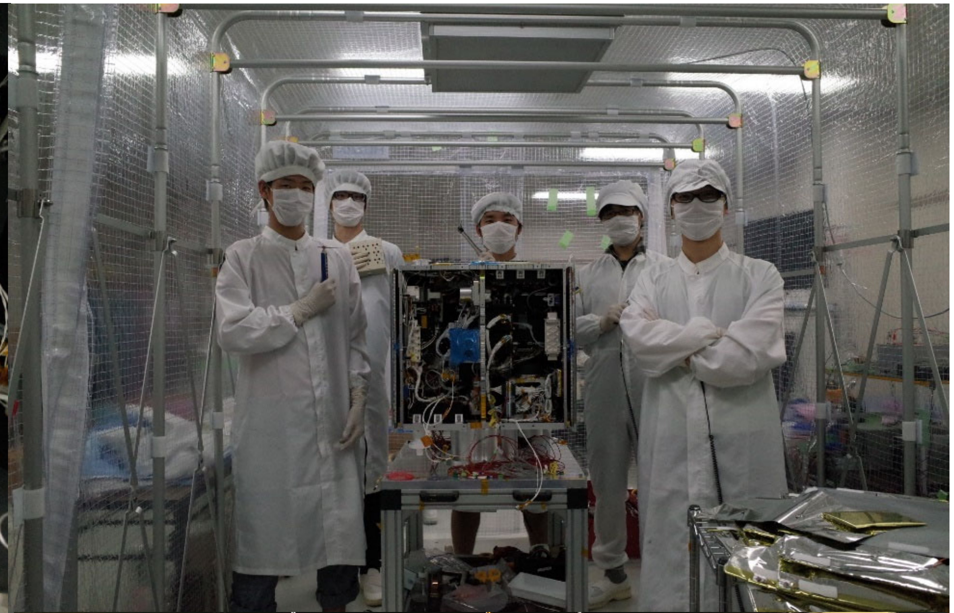
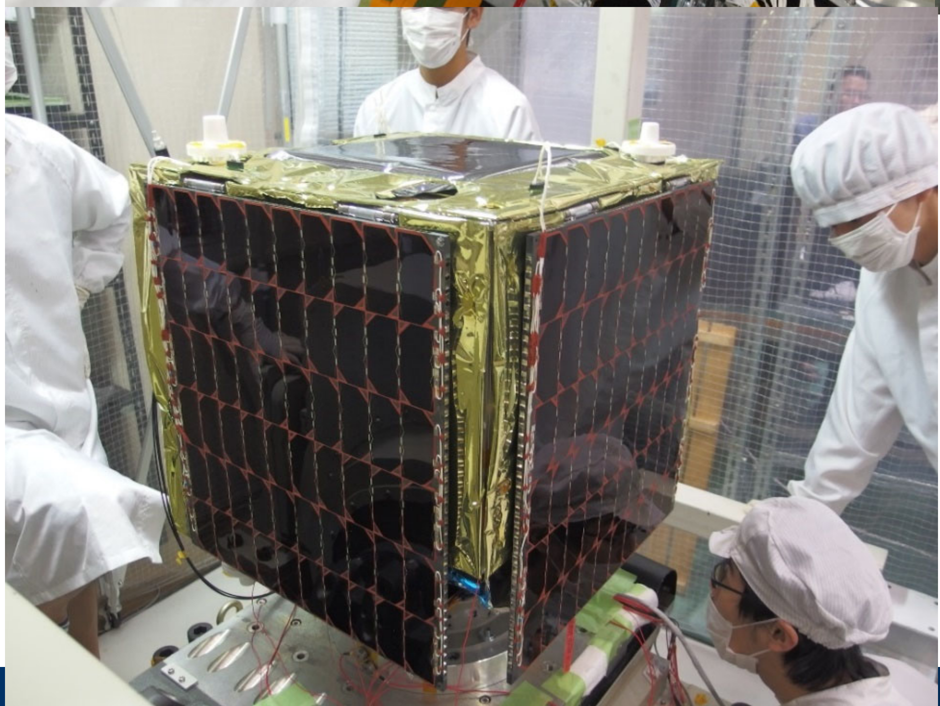
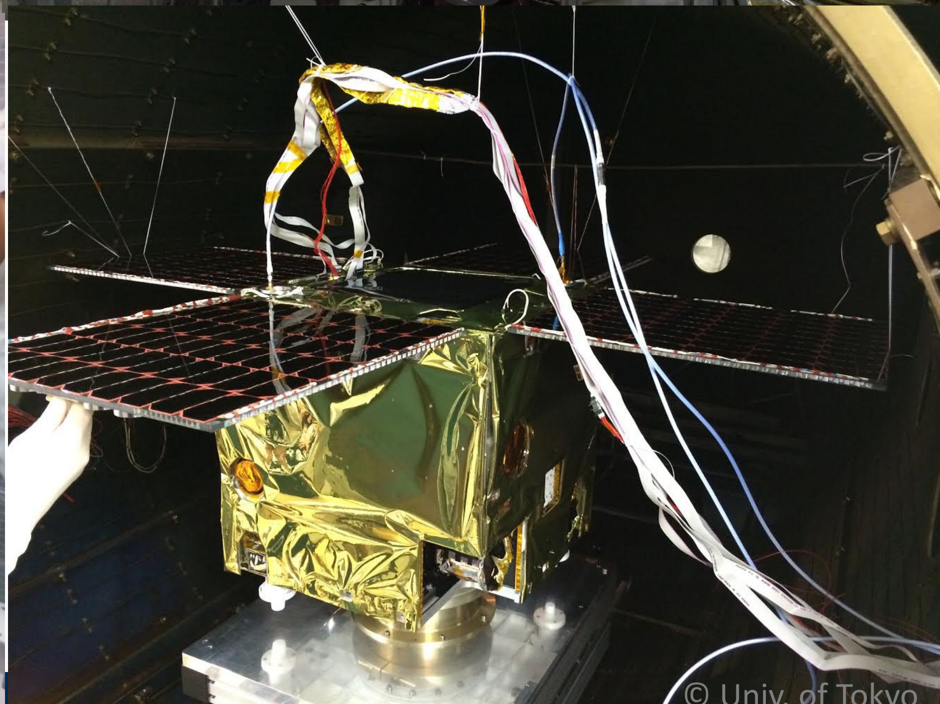
Manufacturer: Addnics co
Max. output power: +17 d
Receiving level: -150 to -
Coherent ratio: 749/880
Modulation: PCM/PSK/PM
two-way Range &
DDOR (±$0.5F_0$, ±$2F_0$)

X-band Solid State Power Amplifier

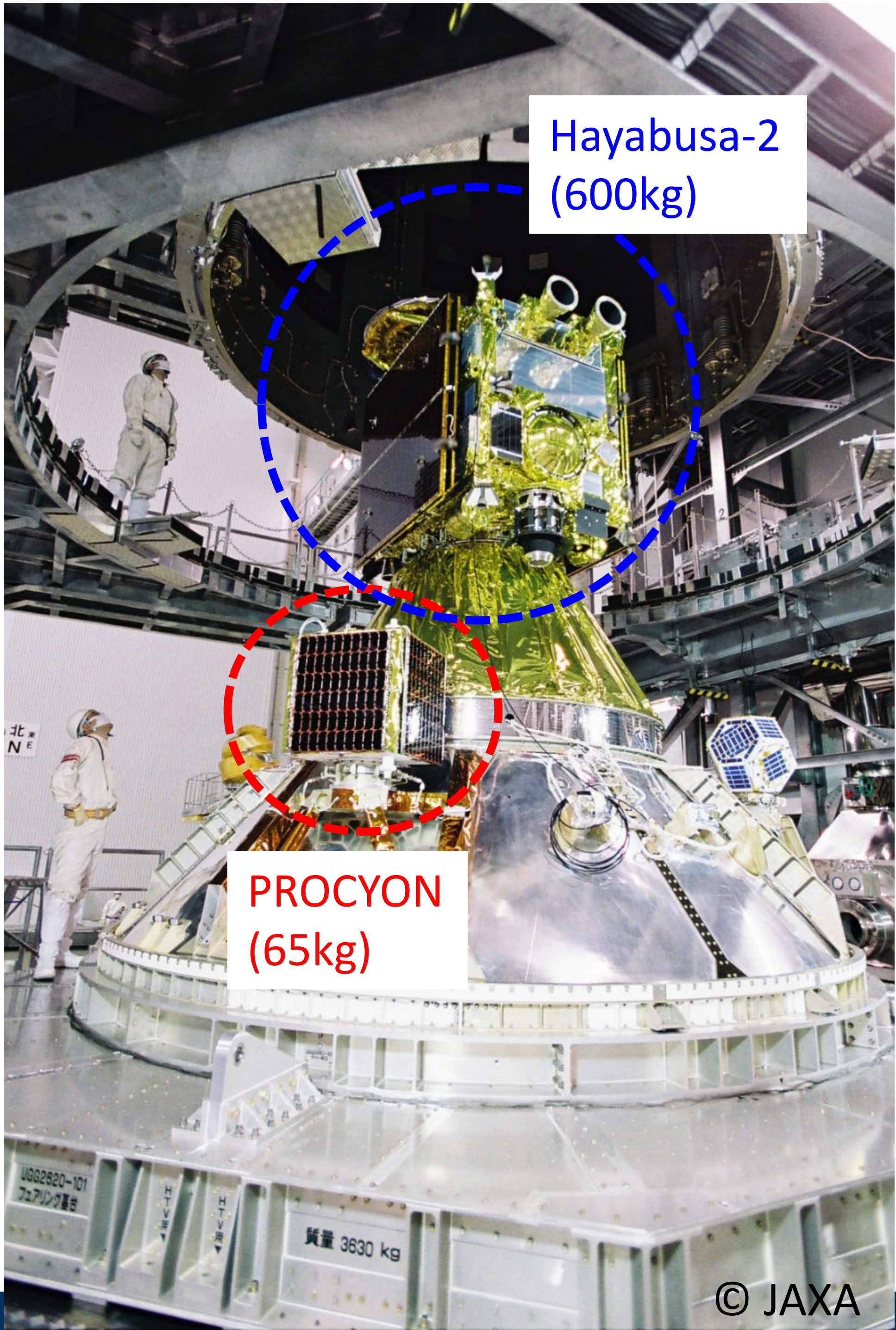
ıcturer: Digital Signal Technologies, inc.
ication device: GaN HEMT
t power: 41.85 ± 0.15 dBm
ncy: > 32.7 % (Max. 35.1 %) (-20 to +60°C)

RF Output > 15W (similar to Hayabusa2)
Efficiency > 32.7% (world's highest)

How PROCYON was developed

Piggyback launch with Hayabusa2 (Dec. 2014)



PROCYON's achievements (2014-15)

Demonstration of deep space bus system
including deep space communication (60M km, 0.4AU) and trajectory guidance/navigation/control →success!

Scientific mission →success!

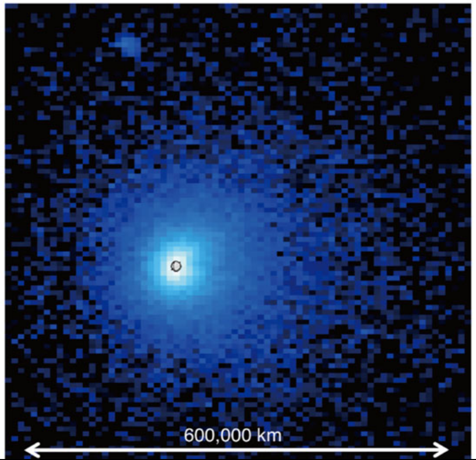
- ✓ **geocorona observation**
- ✓ observation of **hydrogen emission around 67P/C-G**

All the mission were **successful except for**:

- long-time deep space maneuver by the ion thruster
- *actual* asteroid flyby

Within the very limited development time (14 months) and budget (a few M$), we could **demonstrated the capability** of this class of spacecraft to perform deep space mission by itself and it can be a useful tool of deep space exploration.

PRYCYON proved the possibility of deep space exploration by small satellite for the first time in the world.



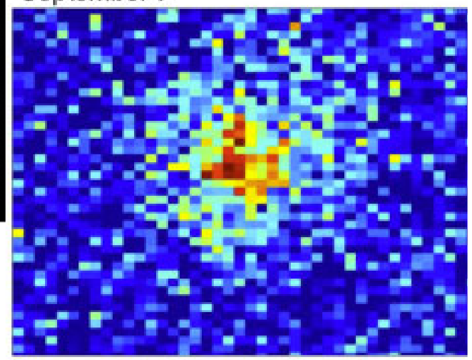
Observed Earth's corona

(Kameda, et al., *Geophysical Research Letters*, 2017)

Comet 67P/Churyumov–Gerasimenko

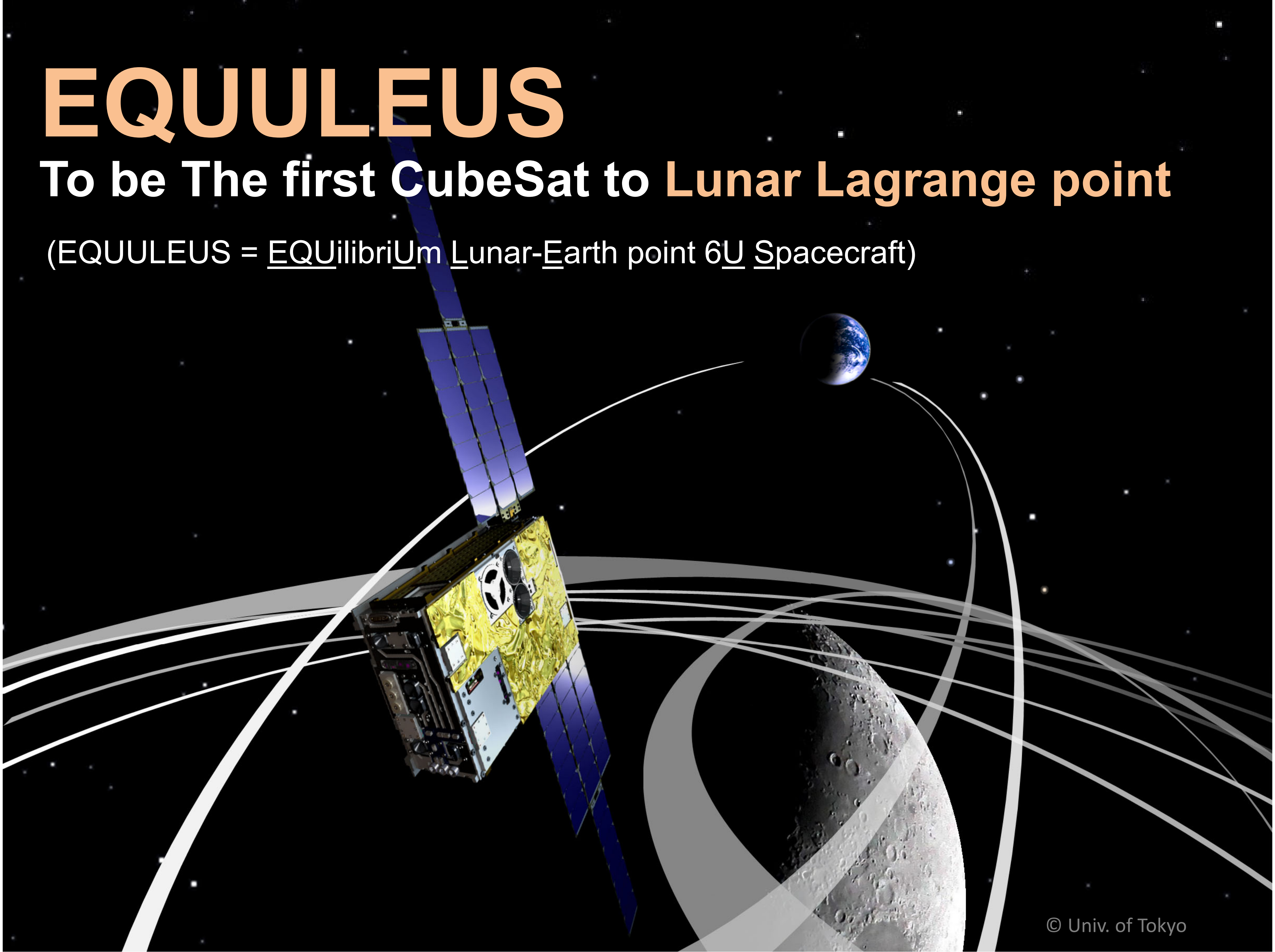
Hydrogen around 67P

©ESA

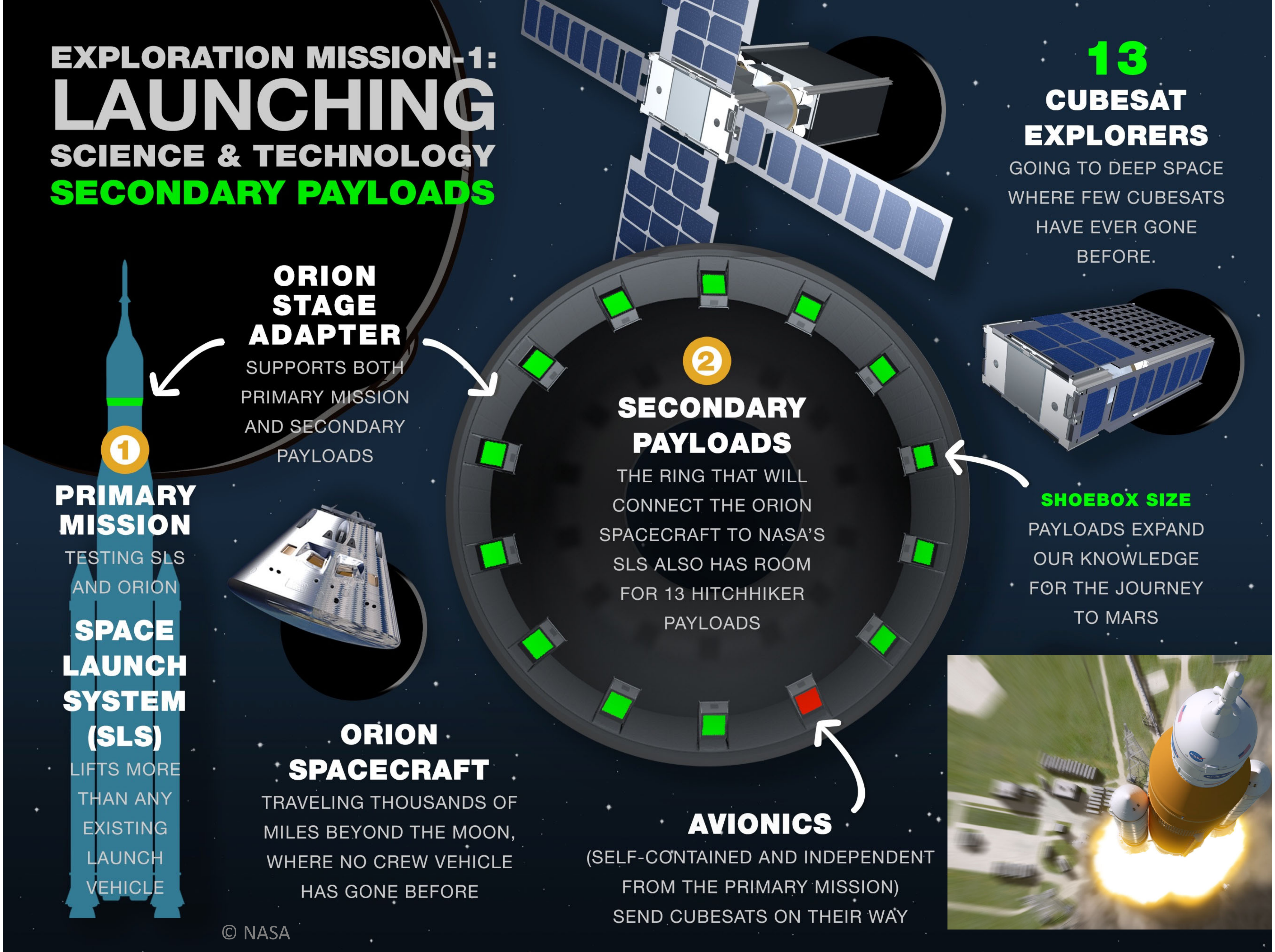


Shinnaka et al., 2017 AJ

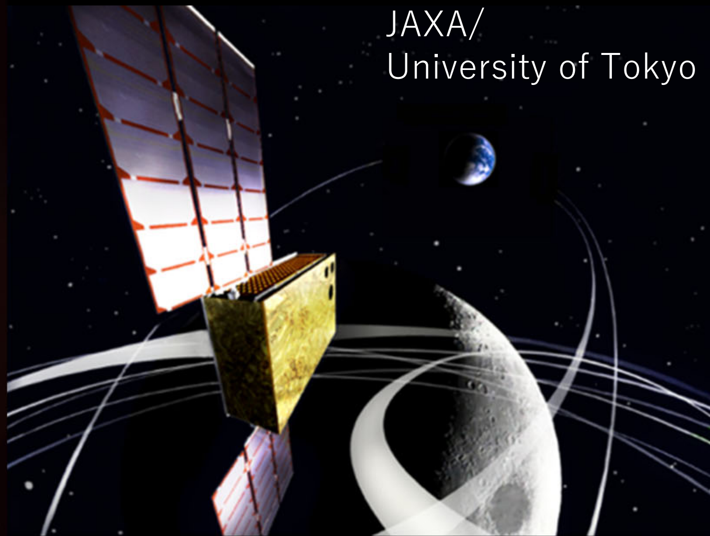
Our next challenge is···

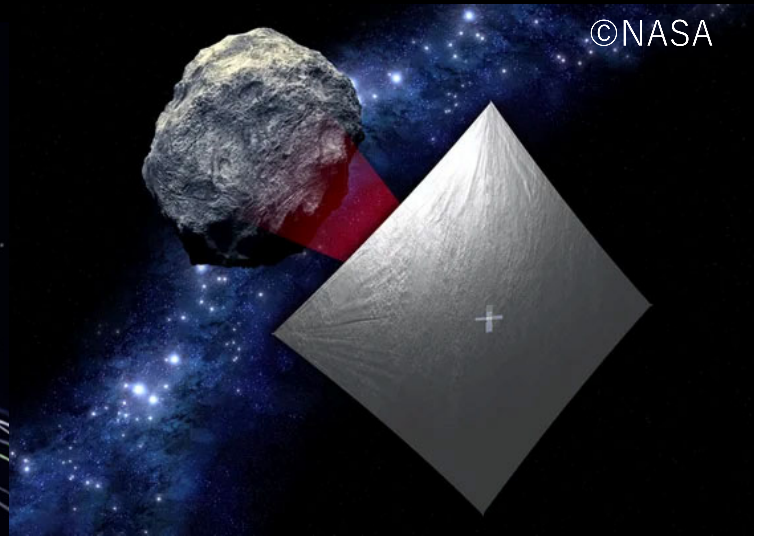

EQUULEUS
To be The first CubeSat to Lunar Lagrange point
(EQUULEUS = EQUilibriUm Lunar-Earth point 6U Spacecraft)
© Univ. of Tokyo

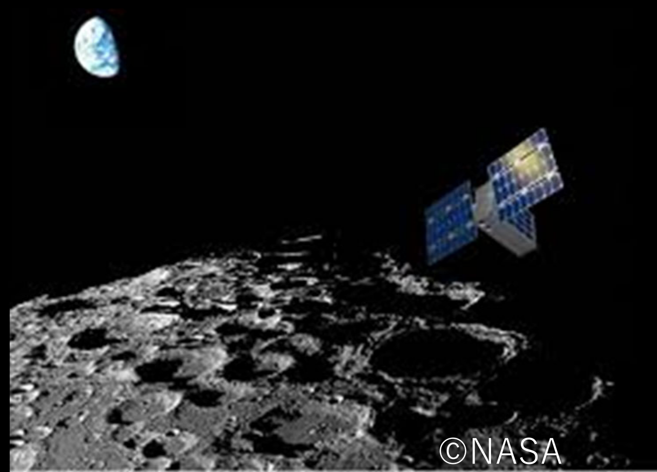
Piggyback launch with the maiden flight of NASA's next generation launch vehicle SLS (Space Launch System)


EXPLORATION MISSION-1:
LAUNCHING
SCIENCE & TECHNOLOGY
SECONDARY PAYLOADS
13
CUBESAT
EXPLORERS
GOING TO DEEP SPACE WHERE FEW CUBESATS HAVE EVER GONE BEFORE.
ORION STAGE ADAPTER
SUPPORTS BOTH PRIMARY MISSION AND SECONDARY PAYLOADS
2
SECONDARY PAYLOADS
THE RING THAT WILL CONNECT THE ORION SPACECRAFT TO NASA'S SLS ALSO HAS ROOM FOR 13 HITCHHIKER PAYLOADS
1
PRIMARY MISSION
TESTING SLS AND ORION
SPACE LAUNCH SYSTEM (SLS)
LIFTS MORE THAN ANY EXISTING LAUNCH VEHICLE
SHOEBOX SIZE
PAYLOADS EXPAND OUR KNOWLEDGE FOR THE JOURNEY TO MARS
ORION SPACECRAFT
TRAVELING THOUSANDS OF MILES BEYOND THE MOON, WHERE NO CREW VEHICLE HAS GONE BEFORE
AVIONICS
(SELF-CONTAINED AND INDEPENDENT FROM THE PRIMARY MISSION) SEND CUBESATS ON THEIR WAY
© NASA

~~13~~ 10 CubeSats on board







Missions of EQUULEUS

1. [Engineering] **primary mission**
   demonstration of **the trajectory control techniques within the Sun-Earth-Moon region** by a nano-spacecraft through the flight to the second Earth-Moon Lagrange point L2 (EML2)

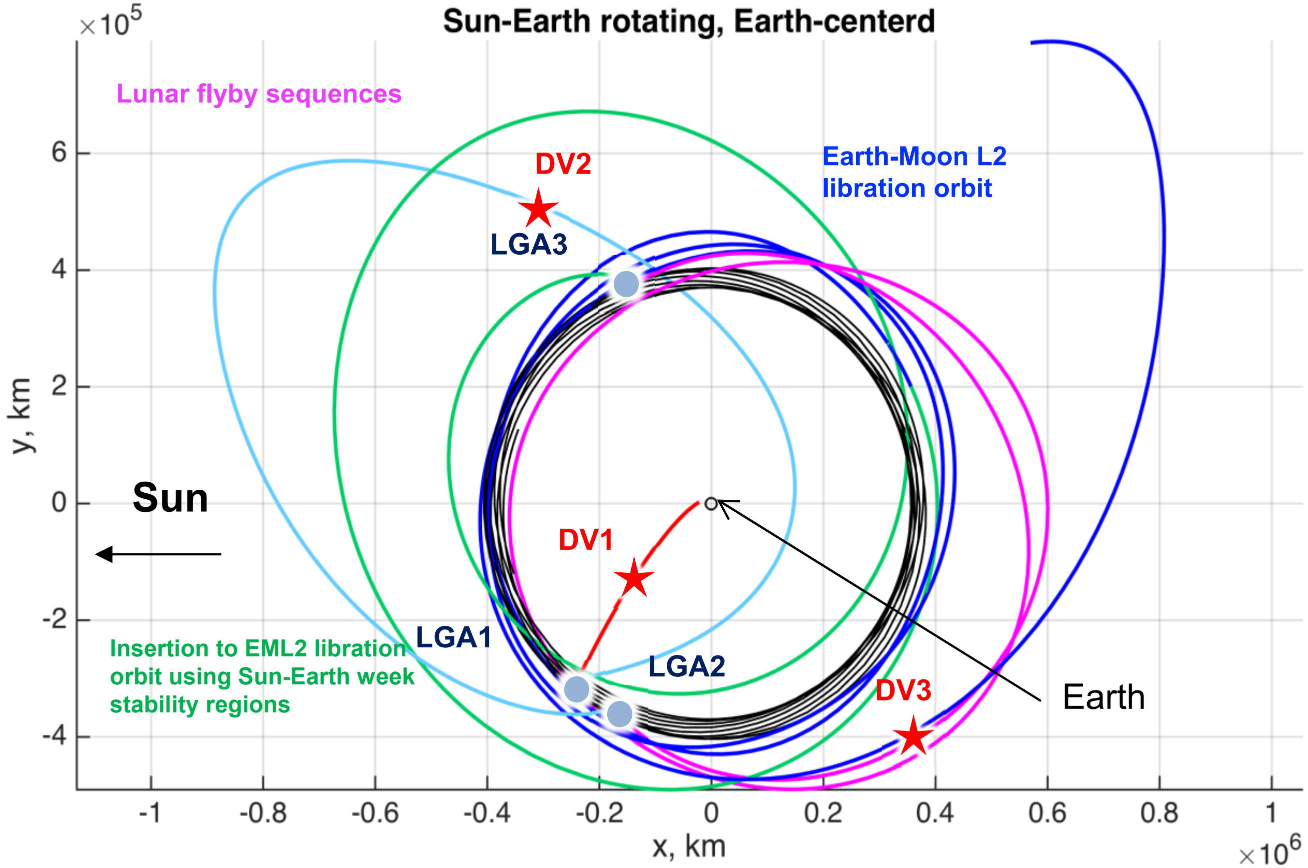
2. [Science #1] (instrument name: **PHOENIX**)
   Imaging observation of the **Earth's plasmasphere**

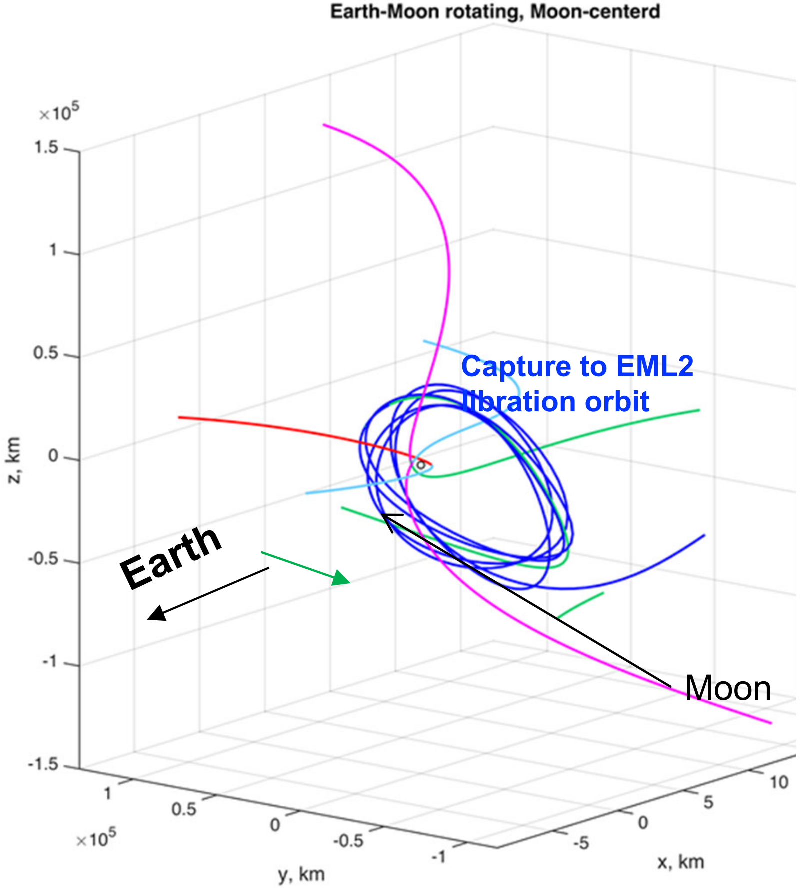
3. [Science #2] (**DELPHINUS**)
   Lunar impact flashes observation

4. [Science #3] (**CLOTH**)
   Measurement of **dust environment in the cis-lunar region** by PVDF film sensors

Trajectory all the way to EML2...

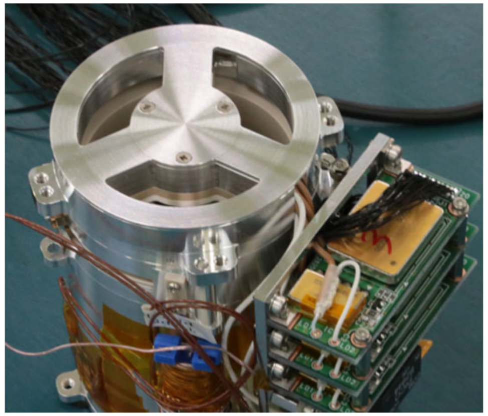
EQUULEUS will perform **6-month ~ 1.5-year flight to EML2** with ΔV of **as low as several tens of m/s** (deterministic), by using **multiple lunar gravity assists**.





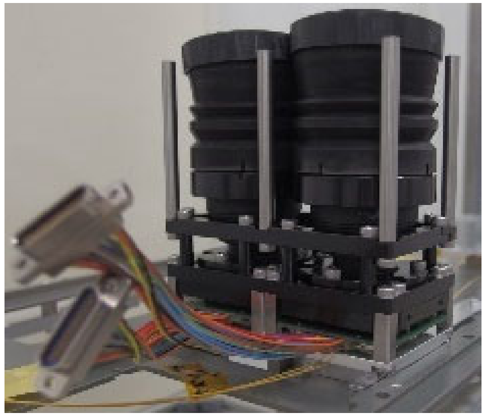
*LGA: Lunar Gravity Assist, EML2: Earth-Moon L2 point

Science missions/instruments of EQUULEUS



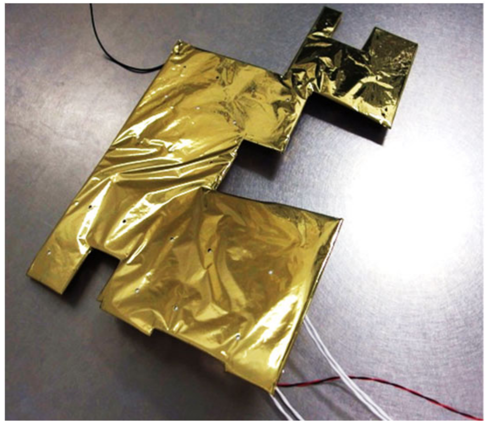
PHOENIX 地球磁気圏プラズマ撮像
(Plasmaspheric Helium ion Observation by Enhanced New Imager in eXtreme ultraviolet)

- Primary science mission of EQUULEUS
- Extreme ultra violet imager to observe the Earth plasmasphere



DELPHINUS 月面衝突閃光観測
(DEtection camera for Lunar impact PHenomena IN 6U Spacecraft)

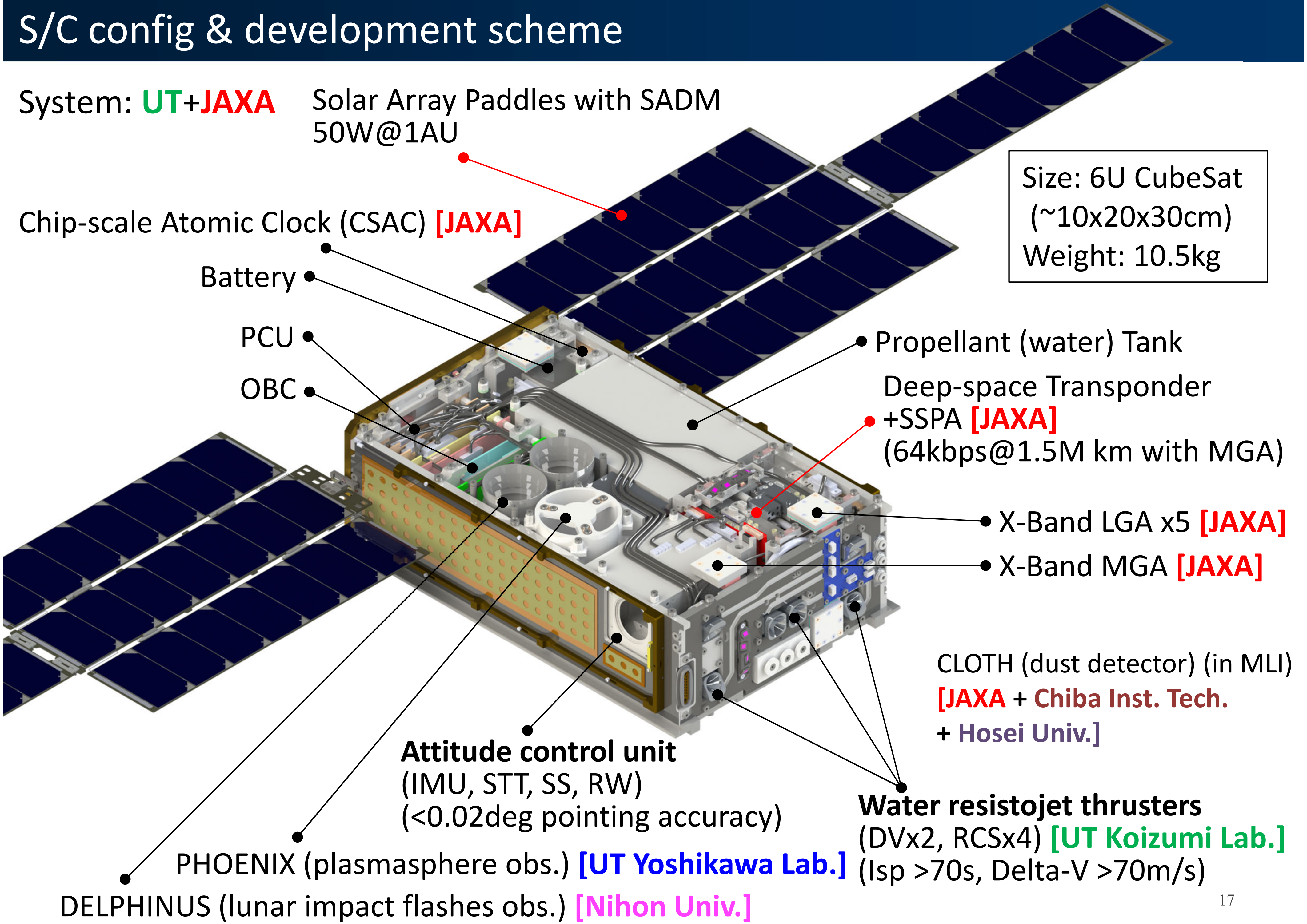
- Optical detector of lunar impacts on the dark side of the Moon from Earth-Moon L2 point
- Plan to install 2 detectors to reduce misdetections



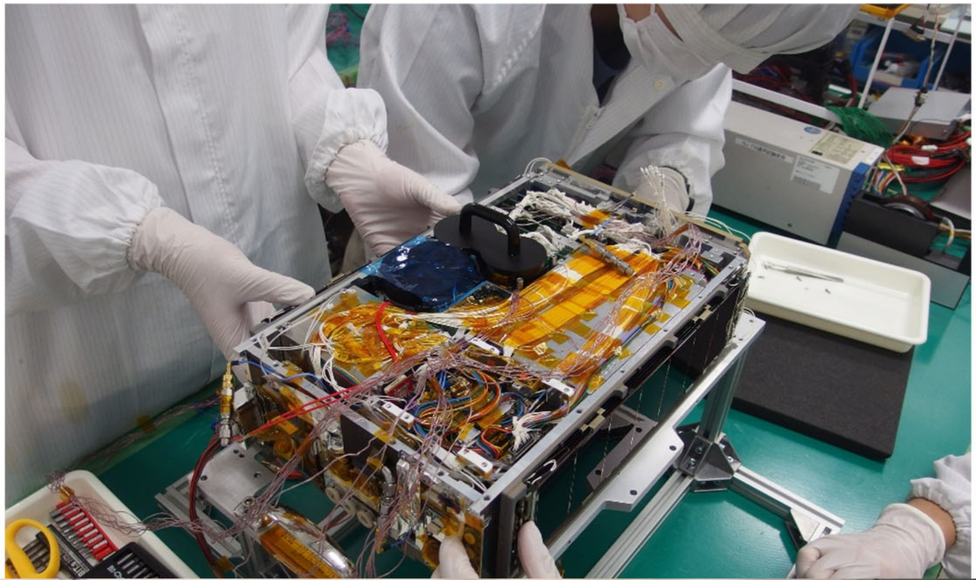
CLOTH 地球ー月圏ダスト検出
(Cis-Lunar Object detector in THermal blankets)

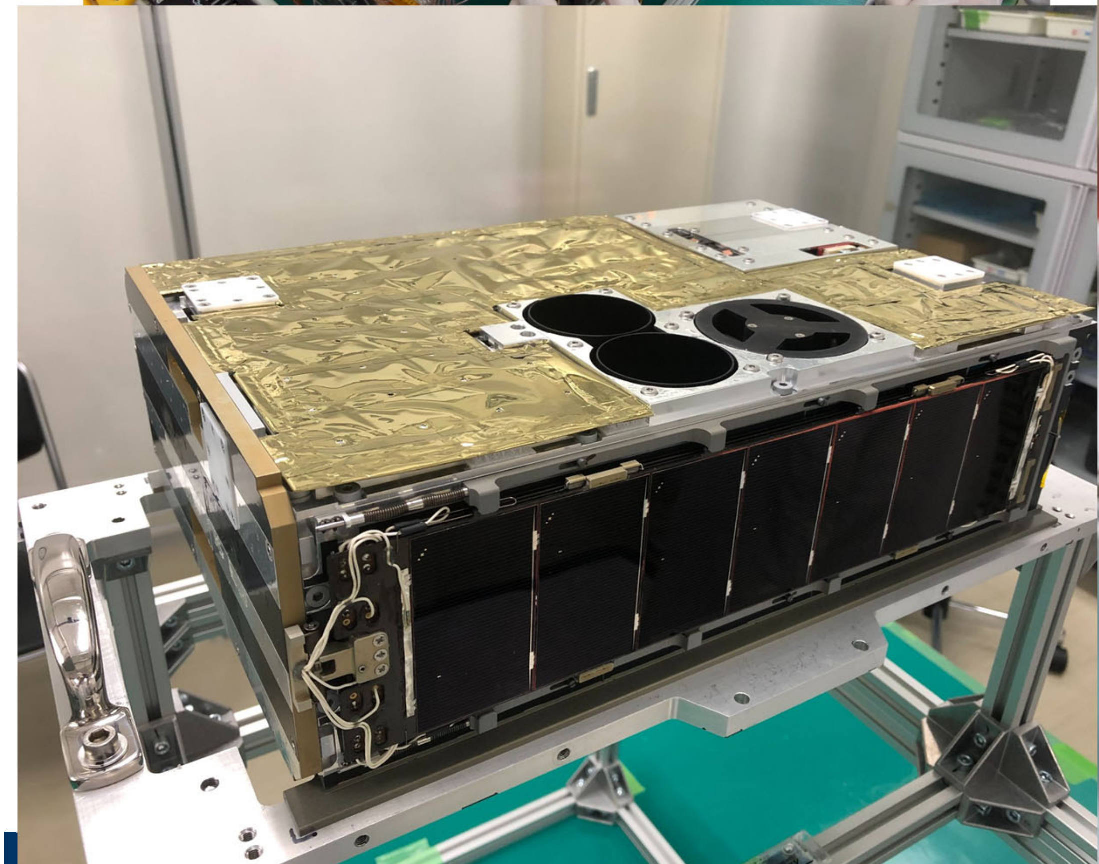
- Detector of small objects in the cis-lunar space
- Thin-film dust detector contained in and combined with the EQUULEUS's MLI (Multi-Layer Insulation)

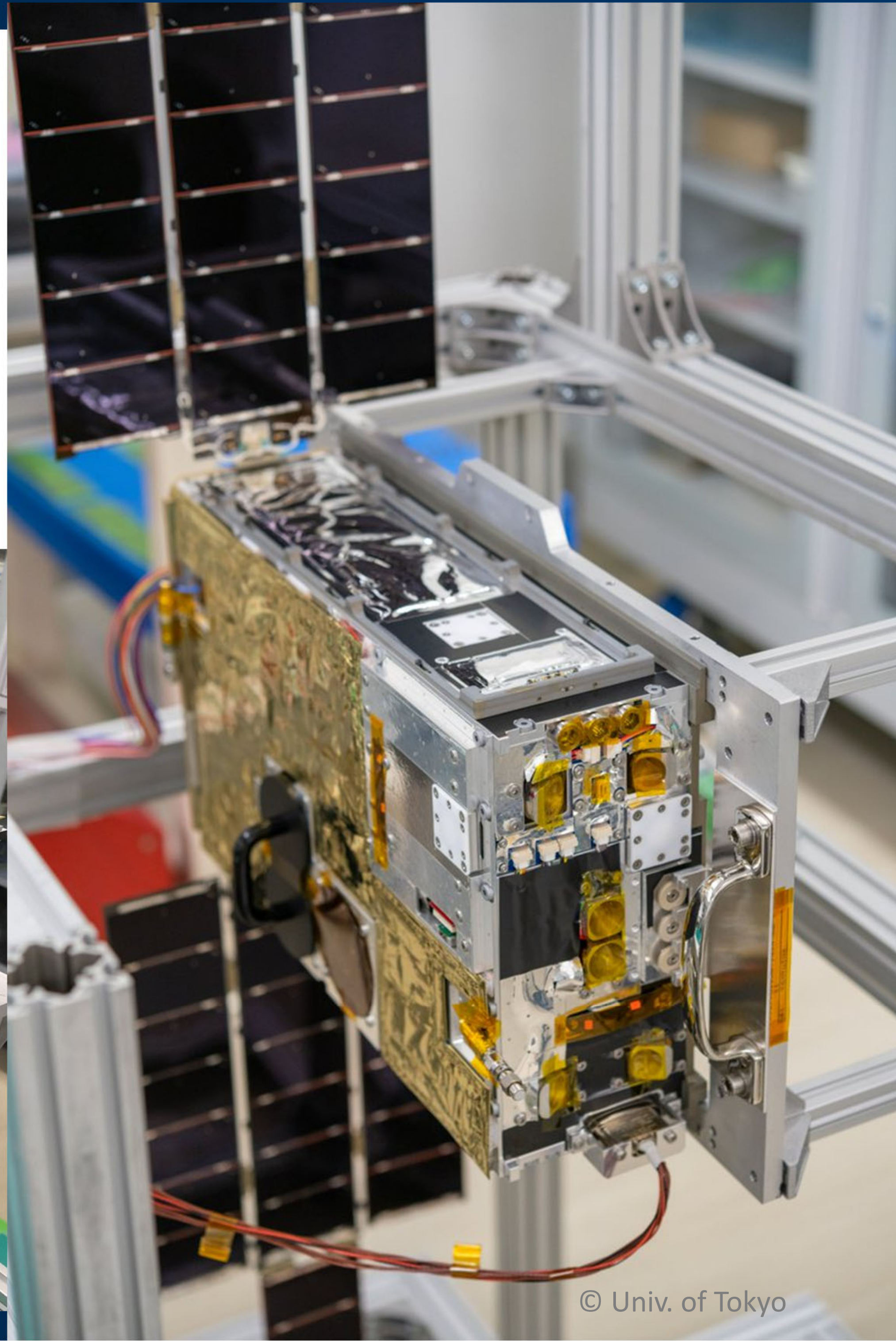
S/C config & development scheme



Flight model development



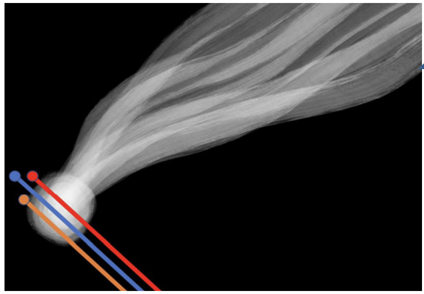




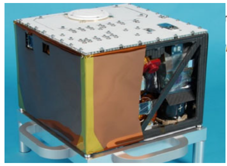
Future directions?

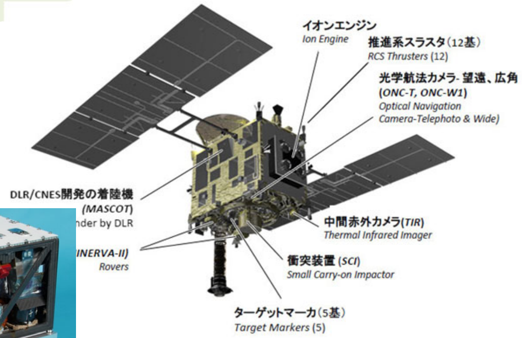
Future directions?

Multi-spacecraft missions



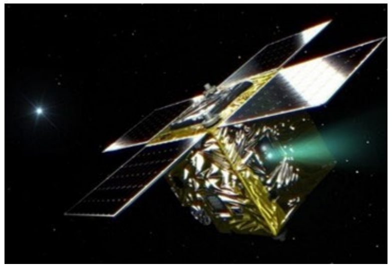
Comet Interceptor ('28)



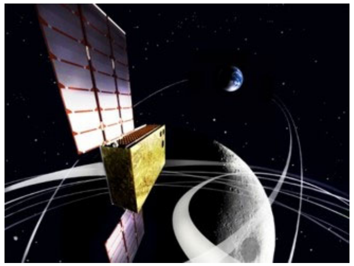


Hayabusa2 + MASCOT ('14)

CubeSat/Micro-Sat deep-space bus (Comm. & in-space propulsion)



Micro-sat bus (PROCYON, '14)

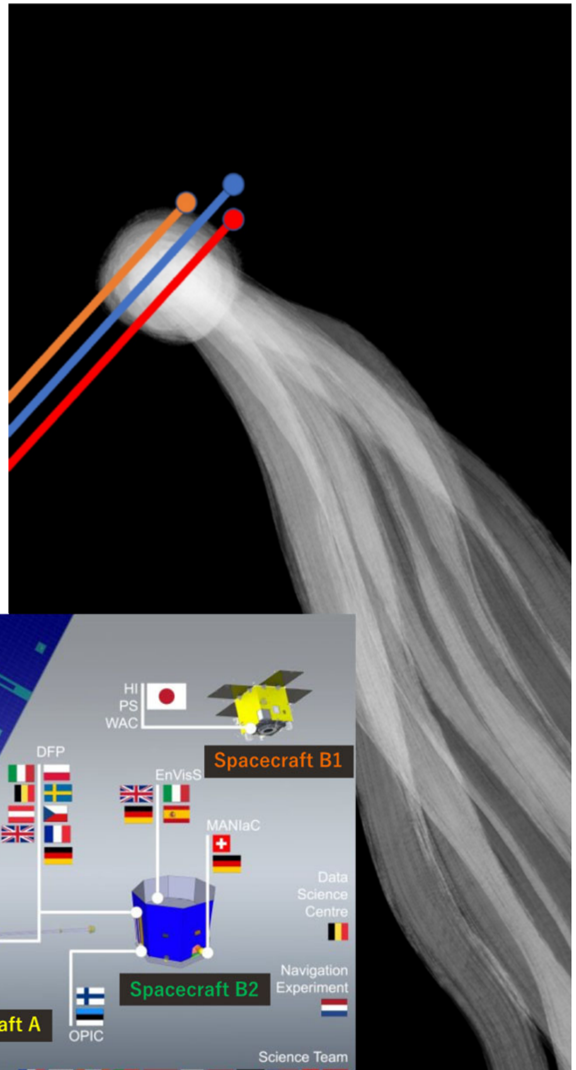


CubeSat bus (EQUULEUS, '22)

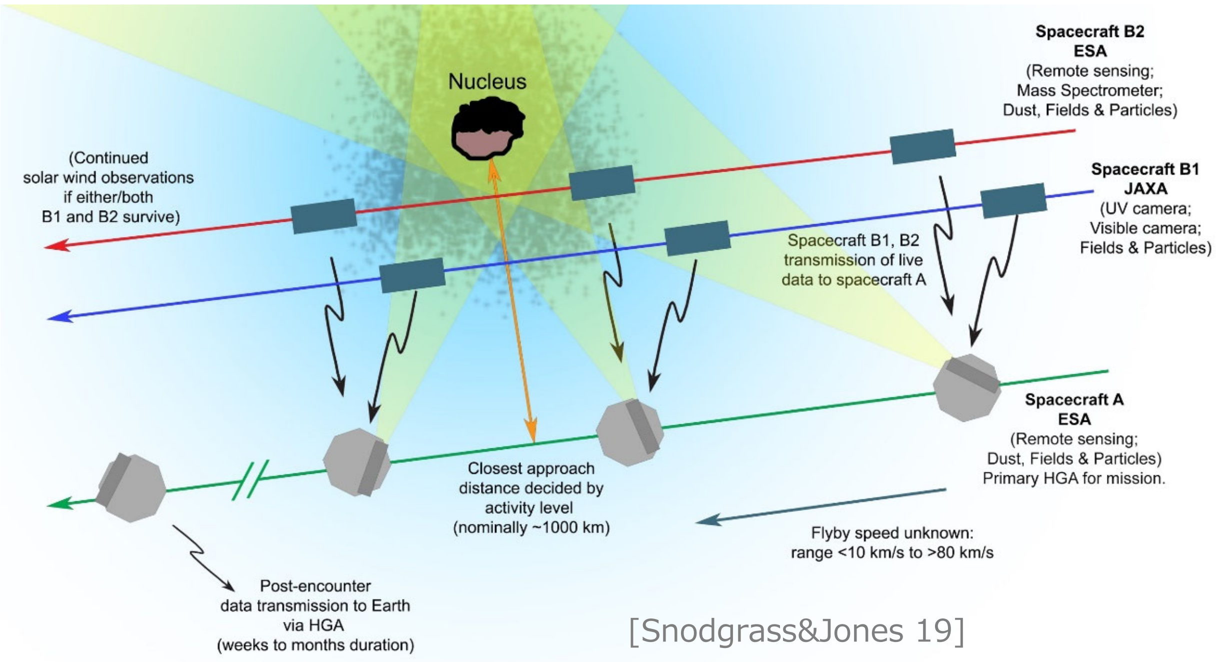
Comet Interceptor:

A Mission to a Dynamically New Solar System Object

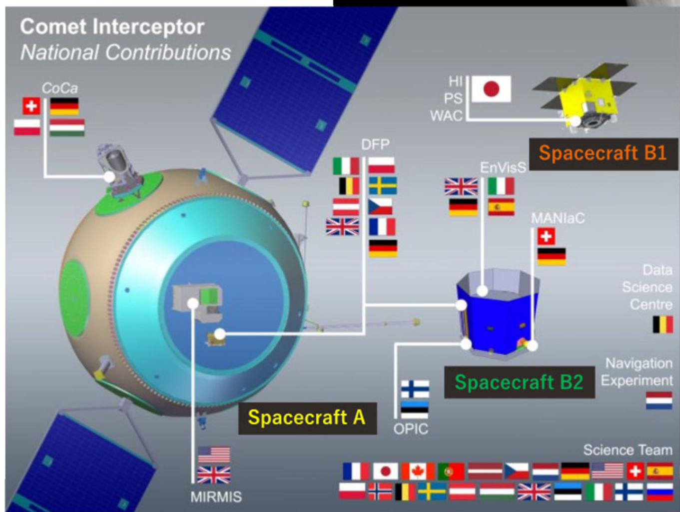
PI: Geraint Jones (Mullard Space Science Laboratory, University College London, UK)
National Co-I in Japan: Ryu Funase (ISAS/JAXA & Univ. of Tokyo)



- Primary science goal is to characterize a **dynamically-new (thus pristine) comet** including its surface composition, shape, structure, the composition of its gas coma, and comet-solar wind interaction, **by at least three spacecraft elements working together**
- Spacecraft will stay at L2 for up to 2-3 years, until a suitable target is identified
- Japan's contribution: One daughter-craft "B1" (with science instr.)



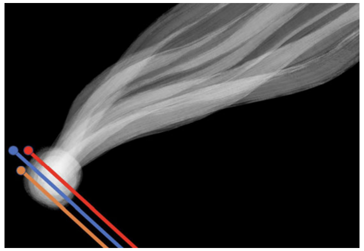
[Snodgrass&Jones 19]



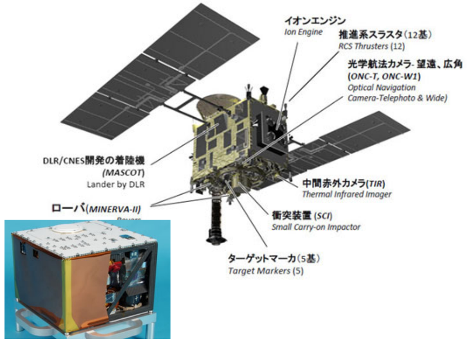
Another direction?

Multi-spacecraft missions

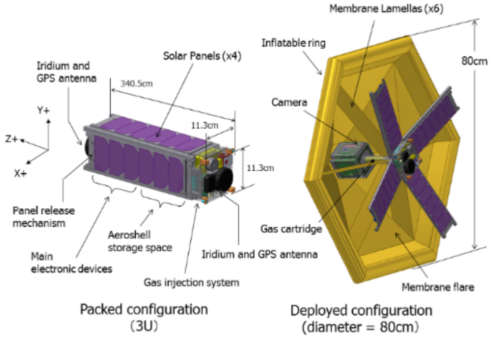
Orbiter/Lander missions



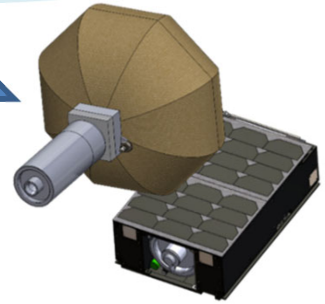
Comet Interceptor (‘28)



Hayabusa2 + MASCOT (‘14)

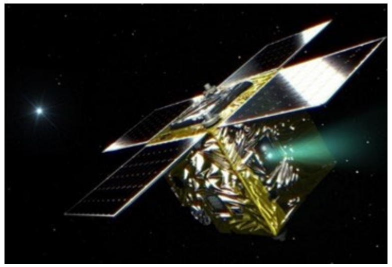


Deployable aeroshell (EGG (‘17), BEAK (‘22))

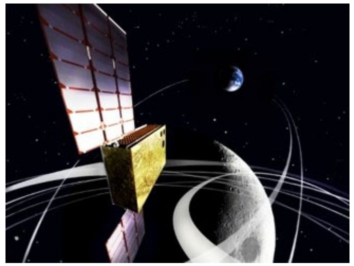


(Solid motor +) semi-hard landing (OMOTENASHI (‘22))

CubeSat/Micro-Sat deep-space bus (Comm. & in-space propulsion)



Micro-sat bus (PROCYON, ‘14)

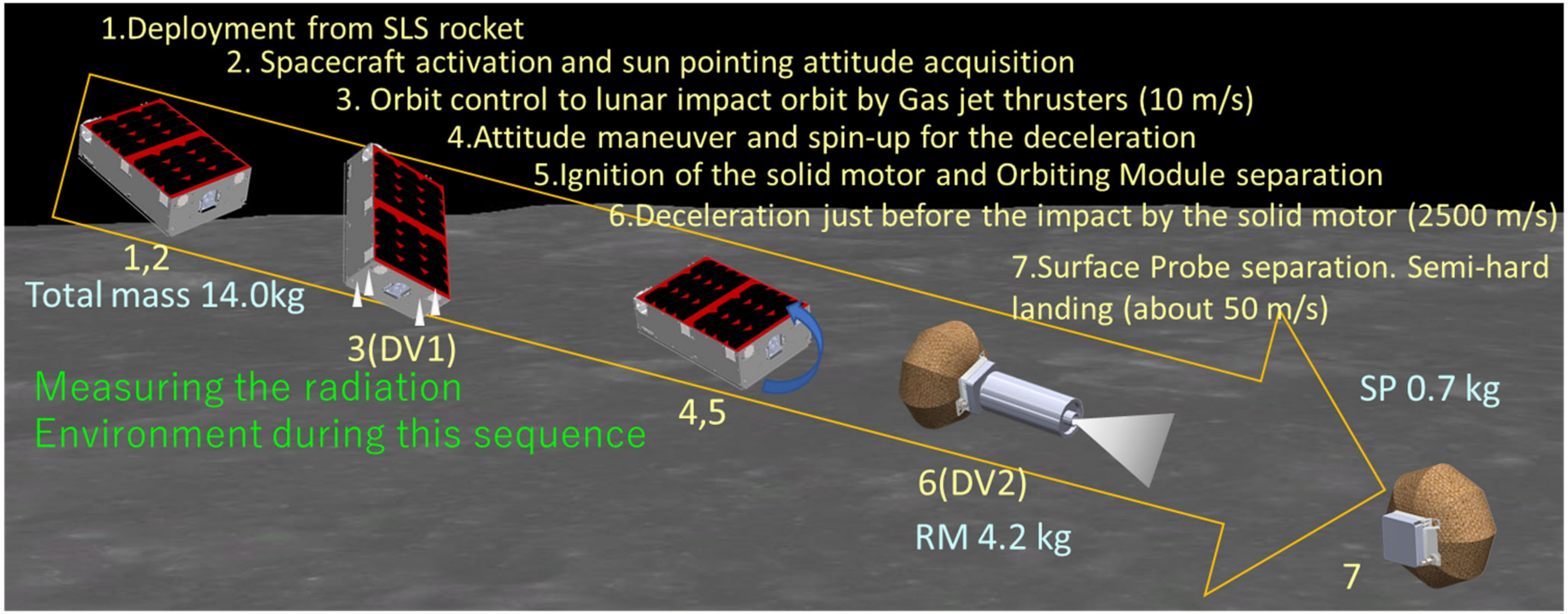


CubeSat bus (EQUULEUS, ‘22)

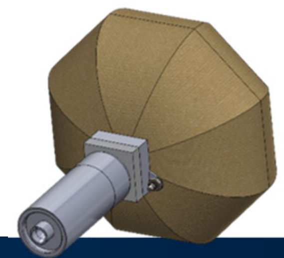
Semi-hard landing demo by "OMOTENASHI"

(**O**utstanding **MO**on exploration **TE**chnologies demonstrated by **NA**no **S**emi-**H**ard **I**mpactor)

*The **smallest moon lander** (launched by the most powerful rocket in the world = SLS), which will demonstrate the key technology for the **multi-point exploration by distributed cooperative nano-scale probes**.*



Whole spacecraft
(6U)



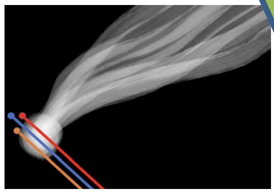
Solid rocket
+Air bag
+Surface probe

Yet another direction?

Multi-spacecraft missions

Orbiter/Lander missions

Frequent deep space missions



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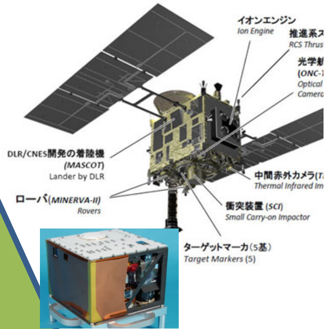
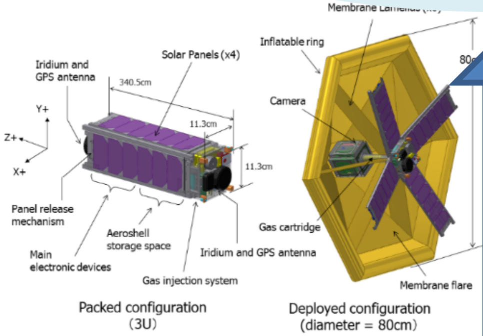
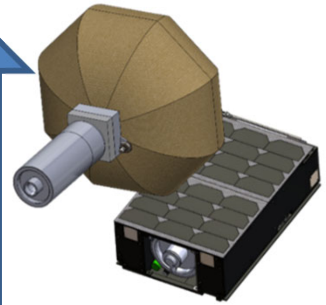


Hayabusa2 +MASCOT ('14)

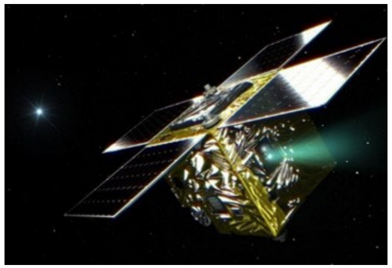


Deployable aeroshell (EGG ('17), BEAK ('22))

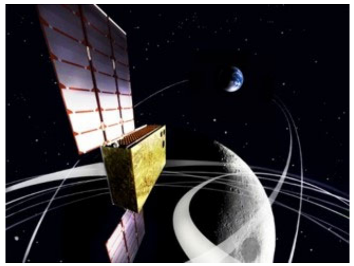


Solid motor, semi-hard landing (OMOTENASHI ('22))

CubeSat/Micro-Sat deep-space bus (Comm. & In-space propulsion)



Micro-sat bus (PROCYON, '14)

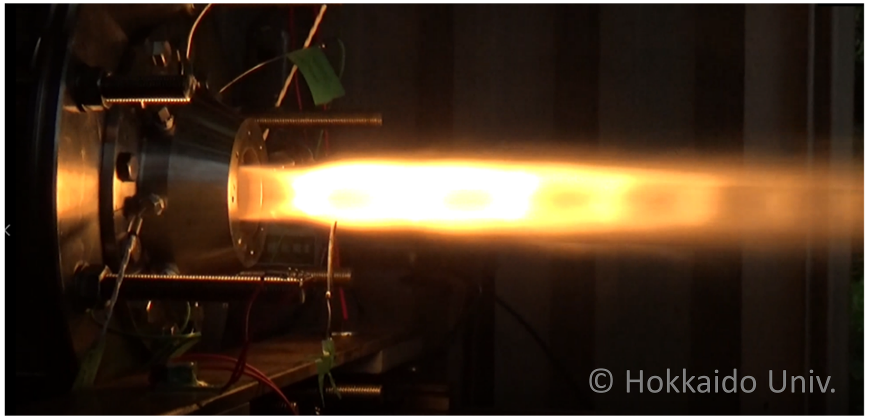


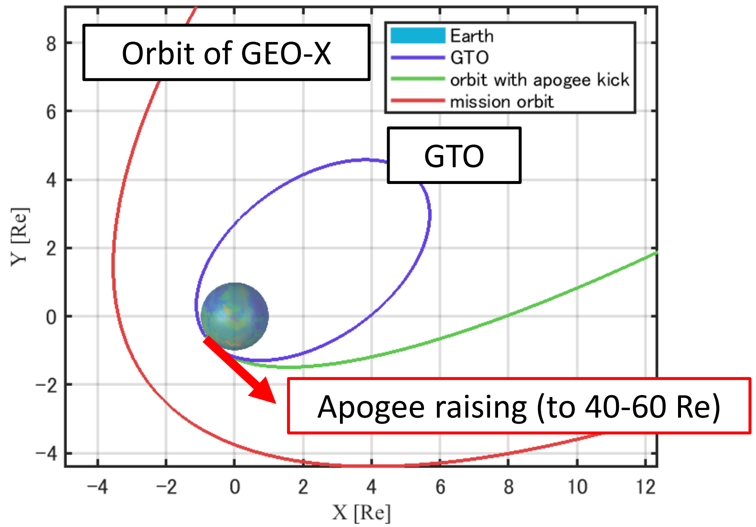
CubeSat bus (EQUULEUS, '22)

Frequent & easy access to deep space

Barriers to frequent access to deep space
= Limitation of launch opportunity

Escape to deep space from Earth orbit (e.g. GTO), where launch frequency can be secured, using a small kick motor (high ΔV propulsion system).





Apogee raising maneuver by hybrid kick motor

Future directions

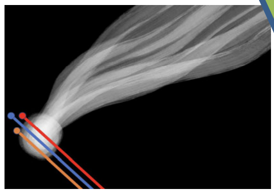
Multi-spacecraft missions

Orbiter/Lander missions

Frequent deep space missions

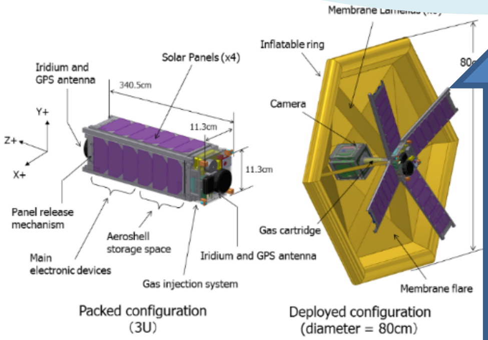
#4

#5

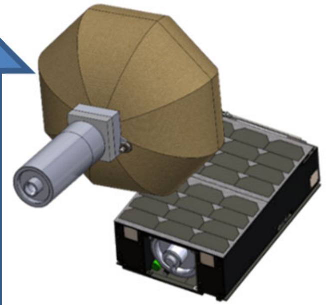


Comet Interceptor ('28)

Hayabusa2
+MASCOT ('14)



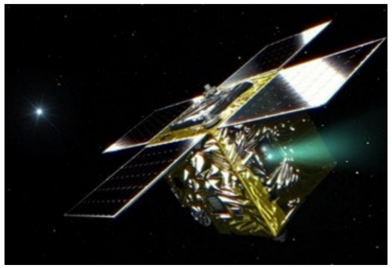
Deployable aeroshell
(EGG ('17), BEAK ('22))



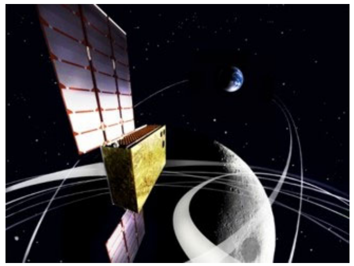
Solid motor,
semi-hard landing
(OMOTENASHI ('22))

Quick, Low-cost,
Light-weight

CubeSat/Micro-Sat deep-space bus
(Comm. & In-space propulsion)



Micro-sat bus (PROCYON, '14)



CubeSat bus (EQUULEUS, '22)