Flight Model Design and Development Status of the Earth—Moon Lagrange Point Exploration CubeSat “EQUULEUS” Onboard SLS EM-1

Ryu Funase
Associate Professor, EQUULEUS project manager, Univ. of Tokyo/JAXA
EQUULEUS Project Team (U of Tokyo, JAXA)
LEO CubeSat/Micro-Sat Fleet
by Intelligent Space Systems Laboratory, The University of Tokyo

XI-IV (2003): 1kg
**The first CubeSat**
Still operational (>15yrs)

XI-V (2005): 1kg
Tech. demo.
Still operational (>12yrs)

PRISM (2009): 8kg
Remote sensing (20m GSD)
Still operational (>8yrs)

Nano-JASMINE: 33kg
Astrometry
(space science mission)
Awaiting launch…

Hodoyoshi-1, 3, and 4 (2014): ~60kg
Remote sensing (~6m GSD)
In operation (>4yrs)

TRCOM-1R (2018): 3kg
Store & Forward
In operation
6m GSD (ground surface distance) image taken by 50kg-class satellite “Hodoyoshi-4” in 2014
What is the next frontier for small satellites?
Deep Space Exploration
The First Interplanetary Full-scale Micro-Satellite

PROCYON
Missions of PROCYON

**Primary mission**
- Demonstration of a micro-spacecraft bus system for deep space exploration

**Secondary, advanced missions**
- GaN-based high efficiency SSPA
- Novel orbit determination method ("chirp DDOR")
- Earth swing-by and trajectory correction to target an asteroid flyby
- Optical navigation and guidance to an asteroid
- Image-feedback control to track asteroid during close fast flyby

**Scientific observation mission**
- Wide-view imaging observation of geocorona (ultra-violet emission from hydrogen atmosphere around the Earth) with Lyman alpha imaging telescope from a vantage point outside of the Earth’s geocorona distribution

---

1. Launch (Dec. 3, 2014 together with Hayabusa-2)
2. Earth swingby (Dec. 2015)
3. Asteroid flyby (Jan. 2016 or later)

2000 DP107 (binary NEA)
# Spacecraft specifications

<table>
<thead>
<tr>
<th>Structure</th>
<th>Size</th>
<th>0.55m × 0.55m × 0.67m + 4 SAPs (Solar Array Panels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>&lt;70 kg (wet)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power</th>
<th>SAP</th>
<th>Triple Junction GaAs, &gt;240 W (at 1 AU, θs = 0, BOL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAT</td>
<td>Li-ion, 5.3 Ahr</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AOCS</th>
<th>Actuator</th>
<th>Reaction Wheels (RW) × 4, Three-axis Fiber Optic Gyro (FOG) × 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor</td>
<td>Star Tracker (STT) × 1, Non-spin Sun Aspect Sensor (NSAS) × 5</td>
<td></td>
</tr>
<tr>
<td>Performance</td>
<td>Telescope (for optical navigation relative to the asteroid)</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>&lt;0.002 [deg/s], &lt;0.01 [deg] (pointing stability)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Propulsion</th>
<th>RCS</th>
<th>Xenon cold-gas jet thrusters × 8, ~22mN thrust, 24s Isp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion propulsion</td>
<td>Xenon microwave discharge ion propulsion system</td>
<td></td>
</tr>
<tr>
<td>Propellant</td>
<td>0.3 mN thrust, 1000s Isp, ~400m/s DV capability (for 65 kg s/c)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.5 kg Xenon (shared by RCS and ion propulsion)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Communication</th>
<th>Frequency</th>
<th>X-band (for deep space mission)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna</td>
<td>HGA × 1, MGA × 1, LGA × 2 (for uplink), LGA × 2 (for downlink)</td>
<td></td>
</tr>
<tr>
<td>Output power</td>
<td>&gt;15 W (RF output), &gt;30 % (GaN XSSPA; world’s highest)</td>
<td></td>
</tr>
<tr>
<td>Orbit determination</td>
<td>Range, Range Rate, DDOR (Delta Differential One-way Range)</td>
<td></td>
</tr>
</tbody>
</table>

| Payload | Weight | ~10 kg (asteroid observation camera+Lyman alpha imager) |
How PROCYON was developed
Ion thruster test in vacuum chamber
Ion thruster test in vacuum chamber
PROCYON’s achievements

Demonstration of deep space bus system including deep space communication (60M km) 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.

PRACYON proved technical readiness to deep space exploration by small satellite for the first time in the world.

(Kameda, et al., Geophysical Research Letters, 2017)
Our next challenge is...
EQUULEUS
To be The first CubeSat to Lunar Lagrange point
(EQUULEUS = EQUilibrium Lunar-Earth point 6U Spacecraft)
EXPLORATION MISSION-1: LAUNCHING SCIENCE & TECHNOLOGY SECONDARY PAYLOADS

13 CUBESAT EXPLORERS
GOING TO DEEP SPACE WHERE FEW CUBESATS HAVE EVER GONE BEFORE.

SHOEBOX SIZE
PAYLOADS EXPAND OUR KNOWLEDGE FOR THE JOURNEY TO MARS

SECONDARY PAYLOADS
THE RING THAT WILL CONNECT THE ORION SPACECRAFT TO NASA’S SLS ALSO HAS ROOM FOR 13 HITCHHIKER PAYLOADS

ORION STAGE ADAPTER
SUPPORTS BOTH PRIMARY MISSION AND SECONDARY PAYLOADS

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

PRIMARY MISSION
TESTING SLS AND ORION SPACE LAUNCH SYSTEM (SLS) LIFTS MORE THAN ANY EXISTING LAUNCH VEHICLE
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 \(~6\) months flight to EML2 with \(\Delta V\) of as low as \(~10\) m/s (deterministic), by using multiple lunar gravity assists.

*LGA: Lunar Gravity Assist, EML2: Earth-Moon L2 point
[Science #1] PHOENIX
(Plasmaspheric Helium ion Observation by Enhanced New Imager in eXtreme ultraviolet)

- **Large structure of He+ in the Earth’s plasmasphere**
  - understanding of the physical process governing the terrestrial plasmas of the Earth

- **Structure of plasmas surrounding the Earth** with respect to the Earth's magnetic field
  - understanding of the escape process of the Earth's atmosphere from the polar region
  - understanding of the evolution of the atmosphere of the Earth and Earth-like planets

![Diagram of PHOENIX spacecraft](image)
[Science #2] DELPHINUS
(DEtection camera for Lunar impact PHenomena IN 6U Spacecraft)

• Lunar impact flashes
  – The flash of light emitted by the high-velocity meteoroids which opportunistically impact on the moon surface

• Near-Earth Asteroids (NEOs)
  – Opportunistic imaging and astrometry of bright NEOs and Temporality Captured Orbiters (TCOs) collaborating with the ground telescope observations.
  – The spacecraft may escape from EML2 and perform flyby imaging of NEOs and TCOs if we are lucky to find an appropriate target.
DELPHINUS (FM)

Image processing board

- **Pixel number**: 659 (H) x 494 (V)
- **Pixel size**: 7.4μm (H) x 7.4 μm
- **Lens (2 pieces)**: f=50mm/F1.4
- **FOV**: 5.58 x 4.19 deg
- **Wavelength**: 400-800nm
- **Lunar impact flash mode**: Exposure = 1/60 sec
- **Asteroid observing mode**: Exposure = 1/4000 ～ 34 sec
- **Limiting magnitude for stars**: 5.5 Vmag with 1/60 sec exposure
- **Limiting magnitude for LIFs**: 4.5 Vmag with 1/60 sec exposure
- **Power consumption**: 0.8 W
- **Dimensions**: 100mm(W) x 50mm(D) x 100mm(H)
- **Operating Temperature**: -10°C ～ +40°C
- **Mass**: 572 g excluding FPGA controller
- **Controller**: FPGA + CPU

60 fps real-time image processing
[Science #3] CLOTH  (Cis-Lunar Object detector in Thermal Insulation)

- Measurement of **dust environment in the cis-lunar region** by PVDF film sensors installed inside the thermal blanket (MLI)

- Scientific objective
  - Revealing the meteoroid environment of the cis-lunar space by collaborative observation with DELPHINUS

- Technological demonstration
  - “Sensorized” MLI for micro-meteoroid impact detection
Solar Array Paddles with SADM (MMA)  
50W@1AU

Chip-scale Atomic Clock (CSAC) (JAXA)

Battery (U. of Tokyo)

PCU (Univ. of Tokyo)

CDH (Univ. of Tokyo with Meisei Electric)

Propellant (water) Tank

Deep-space Transponder  
+SSPA (JAXA)  
(64kbps@1.5M km with MGA)

Attitude control unit  
(IMU, STT, SS, RW) (BCT)  
(<0.02deg pointing accuracy)

Water resistojet thrusters  
(DVx2, RCSx4) (U. of Tokyo)  
(Isp >70s, Delta-V >70m/s)

PHOENIX (plasmasphere obs.) (U. of Tokyo)

DELPHINUS (lunar impact flashes obs.) (Nihon Univ.)
Engineering Model Integration

Intelligent Space Systems Laboratory
The University of Tokyo
Thermal-vacuum test (EM)
Vibration test (EM)
Mass property measurement (EM)
SADA functional test (FM)
LAPSS:
Large-Area Pulse Solar Simulator
LAPSS test (FM)

LAPSS: Large-Area Pulse Solar Simulator
Development status

✓ **Mission approval** by JAXA: April 2016
  (detailed design)

✓ **PDR (internal)**: August - September 2016
  (EM AI&T)

✓ **CDR#1**: July 2017
  (flight model design improvement based on the EM test results)

✓ **CDR#2**: June 2018 *Passed!*
  (FM AI&T) ← *Now!*

• Pre-shipment review: ~April 2019 (under planning)
• Launch: December 2019
XI-IV (2003) by Univ. of Tokyo
The first CubeSat

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

PROCYON (2014) by Univ. of Tokyo+JAXA
The first deep space Micro-Sat
Satellites Launched: 8
Years of In-orbit Satellite Operations: 15
Students Graduated: 104
This room

University Booth U16

Contact
Dr. Ryu Funase
funase@space.t.u-tokyo.ac.jp
Scientific purpose of DELPHINUS

Lunar Impact Phenomena

• Size distribution of large meteoroids in the mass range between tens of grams and tens of kilograms which is as a bridge between visual fireballs (cm-size) and small asteroids (m-size).
• Impact rate during meteor showers and sporadic background compared with Earthly meteor showers.
• Impact rate comparison; near- and far-side of the moon, and leading- and trailing-side of the moon.

Near-Earth Asteroids (NEOs)

• Imaging and astrometry of bright NEOs and Temporality Captured Orbiters (TCOs) corroborating with telescope observations.
• Flyby imaging of NEOs and TCOs if we are lucky!
Technological challenge/advancement

- Miniaturization of the deep space bus (e.g. deep space communication transponder) into the CubeSat form factor

XTRP demonstrated in PROCYON (2014)

**Spec. of our CubeSat X-band deep space transponder**

- **Bit Rate:** 15.625/125/1k [bps] (CMD)
  8 ~ 262.144k [bps] (TLM)
- **Dimension:** 80×80×(<50) [mm], ~0.5U
- **Mass:** < 500 [g]
- **Power:** <13 [W] (@Tx ON)
- **RF output:** 1 [W] (+30 dBm)
- **Navigation:** RARR, DDOR
Technological challenge/advancement

• Development of the new resistojet (warm gas) propulsion system using water as the propellant.
  – Water is perfectly safe, non-toxic propellant, which is advantageous when we consider piggyback launch.
  – (In-situ space resource utilization age in the future is also in my mind...)

4 x RCS thrusters

2 x Delta-V thrusters

Water tank

Vaporization chamber

~2.5U