CubeSats Moon
Exploration with the Japanese
EQUULEUS & OMOTENASHI
Nicola Baresi and International Collaborators

ISSI-BJ & APSCO FORUM on “Science Missions using CubeSats”, Jun 6-8, 2019, Thailand
The New Space Age

“Space is about to get a whole lot more accessible and potentially profitable”

Bloomberg.com

Space Agencies + Private Companies + Universities
= Many Spacecraft Missions

Demonstrate Key Technologies

Exploit New Business Opportunities

Explore the Solar System
The Global Exploration Roadmap

ON TO MARS
- Robotic Mars Sample Return
- Mars Transportation Capabilities
- Goal of Humans on the Martian Surface

MARS SURFACE
- MARS ORBIT

TO THE MOON
- LUNAR SURFACE
- Robotic Resource Prospecting Missions
- LUNAR ORBIT

IN LEO
- EARTH ORBIT
- Deep Space Gateway
- Human Lunar Surface Exploration
- Gateway Moon and Mars Mission Support Operations
- Orion and SLS
- Commercial Transportation Systems
- International Space Station
- Russian Crew Transportation System
- China Space Station
- Future Platforms

How Can CubeSats contribute to our Journey through Space?
Outline

EQUULEUS

OMOTENASHI

MARAUDERS
EQUULEUS
(EQUULEUS = EQUilibriUm Lunar-Earth point 6U Spacecraft)
To be the first CubeSat to the Lunar Lagrangian Point L2
Spacecraft Configuration

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)

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

Propellant (water) Tank
\[ \Delta V \text{ budget: } \sim 80\text{m/s} \]

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

X-Band LGA x5 (JAXA)

X-Band MGA (JAXA)

Water resistojet thrusters
(DVx2, RCSx4) (U. of Tokyo)
\( T = 3.85 \text{ mN}, \text{Isp} = 70\text{s} \)

CLOTH

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

DELPHINUS (lunar impact flashes obs.) (Nihon Univ.)
Plasmaspheric Helium ion Observation by Enhanced New Imager in eXtreme ultraviolet
Lunar Impact Flashes tell us about the size & distribution of near-Earth objects, yet observations from Earth are challenging.

EQUULEUS will monitor the lunar dark portion from the L2 point, hence collecting data from the elusive far side of the Moon.
CLOTH

(Cis-Lunar Object detector in THermal Insulation)

Turn MLI into dust monitors by means of PVDF films installed inside the thermal blankets

**Goal:** characterize dust environment in the cis-lunar region to prepare for future manned missions
## Scientific and Engineering Requirements

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<tr>
<th>Instrument</th>
<th>Requirement</th>
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| **PHOENIX** | • Sun - EQUULEUS - Earth angle > 31 deg  
• Moon - EQUULEUS - Earth angle > 6 deg  
• Observation period > 3 months |
| **DELPHINUS** | • Lunar night region: > 25%  
• Moon - EQUULEUS - Sun angle > 45 deg  
• Lunar altitude: < 60000 km |
| **CLOTH** | • Observation duration > 6 months |

- DV Budget (Transfer + Scientific Operations): **80 m/s**
- EQUULEUS shall be in eclipse for no longer than **30 mins**
Synodic Resonant Halo Orbits (SRHO)

Periodic orbits in the Earth-Moon system that meet scientific goals and avoid eclipses

View from Moon-Sun Rotating frame; See Chikazawa, et al., AAS 2019 for details
Synodic Resonant Halo Orbits (SRHO)
How do we get there?

Launch

- System Checkout
- Orbit determination
- DV1 starts 1.5 day after launch and continues for about 0.5 day to cancel deterministic biases and launch dispersions

Lunar Flyby

- PHOENIX Obs
- Transfer via Luni-solar perturbations (TCMs and clean-up maneuvers are conducted before and after lunar flybys)
- Insertion to EML2 libration orbit

Insert to EML2 Libration Orbit

- DELPHINUS & CLOTH
- Station keeping around EML2 libration orbit
  … and to the extended mission (disposal from EML2)

LEOP is the most critical phase of the mission.

- After just one-two days, the system must be ready for a single-point failure DV
- With limited ground station availability, there is even less time for operations and orbit determination; knowledge errors are also critical for an effective DV1
- Ground station availability during critical LEOP will be one of the main challenges for future deep space exploration by CubeSats
Baseline Trajectory (as of June 2019…)

Total (deterministic)
\( \Delta V: 12.08 \text{ m/s} \)

Insertion into a 1:4 N SRHO

\( \Delta V_1 = 8.12 \text{ m/s} \)
\( \Delta V_2 = 3.87 \text{ m/s} \)
\( \Delta V_3 = 4.08 \text{ cm/s} \)
OMOTENASHI
Outstanding MOon exploration TEnchnologies
demonstrated by NAno Semi-Hard Impactor

❖ World’s Smallest Moon Lander
   6U Cubesat, m = 14 kg

❖ おもてなし: “spirit of selfless hospitality” and
   main slogan of 2020 Tokyo Olympics
Mission sequence

1. Deployment form SLS rocket
2. Spacecraft activation and sun pointing attitude acquisition
3. Orbit control to lunar impact orbit by Gas jet thrusters (10 m/s)
4. Attitude maneuver and spin-up for the deceleration
5. Ignition of the solid motor and Orbiting Module separation
6. Deceleration just before the impact by the solid motor (2500 m/s)
7. Surface Probe separation. Semi-hard landing (about 30 m/s)

Total mass 14 kg
Solid motor 4.3 kg
Surface Probe 0.7 kg
System Configuration and Baseline Trajectory

The Orbiting Module (OM) will be jettisoned @ΔV2 to reduce mass.

Surface Probe (SP) will separate from the Retro-motor Module (RM) @burnout and free-fall from ~1 km.

See Ayuso, et al., Acta Astronautical, 2019
Key Challenges

Trajectory Robustness to Execution and Navigation Errors: Flight Path Angle shall be small to minimize vertical errors

See Ayuso, et al., Acta Astronautical, 2019
MARAUDERS

Small satellite mission to deploy ~ tens of instrumented nano-landers to the Moon’s polar regions and explore physical properties and volatile contents near / inside permanently shadowed regions (PSR)

1) Deployment
2) Deceleration / Acceleration Phase
3) Probes Release
4) Data Collection & Relay

Impact velocities < 300m/s

Ground Station
25 km
Satellite Observations Confirm that Water Ice is present in Lunar PSRs. However…

- **How much water?**
  A few wt% in the top ~10s of cm, possibly covered by dry regolith (neutron data, Lawrence+2017)

  Up to 30 wt% surface-exposed H2O ice in ~3.5% of PSRs (Li+2018)

- **Where is the water?**
  Presence of water is not directly correlated with PSRs or temperature

  Surface ice is detected in only a few PSRs (Li+2018)

- **What is the physical state of the water?**
  No information is available through remote sensing
Measurement Technique

The goal of our deployed nano-impactors will be to relay deceleration and temperature profiles as they penetrate in the lunar regolith.

Surface strength & max shock are related to composition & structure: implicit first-order information about volatile content.

Gertsch et al. (2008)
Current Challenges: Systems and Trajectory

- What’s the optimal system design?
- What’s the optimal trajectory to fulfill our mission goals?
- Feasibility of Concept under Navigation and Communication constraints
Conclusions

❖ CubeSat missions to the Moon have the potential to **advance knowledge of the cis-lunar environment** and **drive innovation** for future deep-space and small-sat missions

❖ EQUULEUS and OMOTENASHI will fly on EM-1 and be the first small satellite in a libration point orbit / smallest lunar semi-hard lander

❖ Trajectories have been designed to meet scientific & engineering requirements / maximize the possibility of successful landing

❖ MARAUDERS is a new concept that needs extensive feasibility and trade-off analyses, but high scientific return

Follow the journey on Social Media!

@EQUULEUS_en   @OMOTENASHI_JAXA
Q?

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EXPLORATION MISSION-1: LAUNCHING SCIENCE & TECHNOLOGY SECONDARY PAYLOADS

1. PRIMARY MISSION
   TESTING SLS AND ORION SPACE LAUNCH SYSTEM (SLS)
   LIFTS MORE THAN ANY EXISTING LAUNCH VEHICLE

2. ORION STAGE ADAPTER
   SUPPORTS BOTH PRIMARY MISSION AND SECONDARY PAYLOADS

3. ORION SPACECRAFT
   TRAVELING THOUSANDS OF MILES BEYOND THE MOON, WHERE NO CREW VEHICLE HAS GONE BEFORE

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

5. SHOEOBOX SIZE
   PAYLOADS EXPAND OUR KNOWLEDGE FOR THE JOURNEY TO MARS

6. 13 CUBESAT EXPLORERS
   GOING TO DEEP SPACE WHERE FEW CUBESATS HAVE EVER GONE BEFORE
**DELPHINUS**

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
OMOTENASHI: Solid Rocket Motor

Retro Motor: 4.3 kg, Isp = 260 s, DV = 2.5 km/s, T = 20s
Decelerates the CubeSat to the Lunar surface.
Volatile Transport in the Solar System:

Permanently Shadowed Regions (PSRs) at the Moon's poles do not see the sun for geologically long timescales.

Temperatures as low as 25 K have been measured inside lunar PSRs.

**Volatile Transport in the Solar System:**

- Elucidate volatile transport in the solar system
- Enable in-situ resource utilization
**MARAUDERS: Payload**

~10x nano-probe of size 10x10x0.5 cm, mass: 0.1 kg. Each probe contains
- ACCelerometer (science instrument)
- Thermometer + Heater
- COMM subsystem for data relay
- EPS with BATteries or capacitors

System block diagram of MARAUDERS nano-probes

COTS alternatives already exist: **Endevco Model 7270A (2018)**
- Linear range up to 200,000g
- Sensitivity 0.5/1 μV/g
- Frequency response: 0 to 150,000 Hz
- Mass: 1.5g
MARAUDERS: Measurement Technique

Small spacecraft equipped with penetrators or inertial measurement units (IMU) can characterize the strength and structure of the planetary surface they impact.

High Heritage!

Penetrometer on Cassini-Huygens:

Mission data returned from Huygens probe landing on Titan. Although the returned data is limited, it gives valuable information on the conditions of an unknown surface.

By calibrating the response of the instrument in the lab to different types of material, compositional information may be inferred from the response of the penetrator.

The maximum shock force is related to the impact speed (known), impactor properties (known), and surface composition (measured).

Max Force 2000 N
(Lorenz 1994)