Trajectory Design for the JAXA Moon Nano-Lander OMOTENASHI

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OMOTENASHI is a JAXA 6U cubesat – 14 kg
Piggyback of SLS EM-1
First nano semi-hard lander on the Moon surface
Deliver package (0.7 kg) to Moon surface From a Moon fly-by orbit
  - Demonstrate landing maneuver using solid rocket motor
  - Demonstrate advanced shock-absorption structures
Challenging mission.
  - Low available resources
  - Demanding trajectory
  - Design robust to errors is paramount
Trajectory Overview (I)
Fly-by altitude: 577 km
Trajectory Overview (IV)

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![Graph showing trajectory of a mission with Earth and Moon coordinates.](image)
Trajectory Overview (V)

(1 deg \sim 30 \text{ km})
13 cubesats delivered by EM-1
Moon flyby/arrival after $\sim$ 6 days. Time for OD is very limited
JAXA requested support from international partners for ground-track coverage and communications
OD vertical position error during landing may jeopardize the mission
- Range and range-rate change slowly during the last 2–3 days of the mission. Poor accuracy
- Use of D-DOR reduces the OD error to acceptable levels
  - (Delta-Differential One-way Ranging)
  - D-DOR requires the use of two ground stations
  - Increased complexity and cost of the mission
DV1 design

- Magnitude. Trade-off
  - Fuel budget
  - Shallow Flight Angle at Moon arrival
  - Size of feasible solutions space
- Azimuth $\phi$, polar angle $\theta$ (J2000Eclip)
  - Grid search with iterative refinement
  - Unfeasible solutions filtering
- DV1 candidates with different Flight Path Angle.
  - We show here case 2 ($FPA = -4$ deg)
  - Cases 1, 3 and 4 in the paper
DV1. Sensitivity analysis

- DV1 error analysis. Transfer success probability
  - Orbit Determination error ($P \simeq 100\%$)
  - DV1 execution error

- Trajectory Correction Maneuver (TCM) must be considered
- TCM designed to re-target original landing location.
- Expected TCM magnitude found to be $\sim 0.15 \text{ m/s}$.
- Navigation accuracy requirement:
- FPA at arrival is effectively controlled.
- Dispersion in along-track direction reduced to $\sim \pm 45 \text{ km}$.
Magnitude, two orientation angles and ignition timing
- Magnitude fixed by solid rocket motor
- Out-of-vertical-plane direction set to 0
- two variables left

We determine the maneuver with two constraints at burnout:
- height over the Moon
- zero vertical velocity

We consider a range of initial heights 80–230 m
DV2 Sensitivity analysis

- DV2 execution and OD error. Monte-Carlo simulation.
- Some of the MC samples crash into the Moon during the solid rocket motor maneuver → failure
- Using local topography, velocity is projected into
  - direction perpendicular to the ground (limit: 30 m/s TBD)
  - direction tangent to the ground (limit: 100 m/s TBD)

The largest contributions come from DV2 orientation, thrust duration and total $\Delta v$ errors
DV2. Reducing critical errors

- Effect of reducing by 50% the critical errors (DV2 orientation, thrust duration and total $\Delta v$ errors)

- Large increment of landing success rate
- Increasing critical velocity to 40 m/s → success rate over 95%
- Under consideration by OMOTENASHI team
  - Hard to achieve. Prioritize safety until DV2 burnout
OMOTENASHI will be the first semi-hard Moon lander
- Injection from Moon fly-by orbit
- Small Flight Path Angle at Moon arrival
- Deceleration with solid rocket motor

Error-robust trajectory is paramount

D-DOR is mission enabling

TCM likely to be needed

Limited landing success rate. Critical error sources identified
- Solid rocket motor thrust duration, orientation and total $\Delta v$

A higher free-fall makes the solid rocket motor maneuver safer
Thank you

Questions?