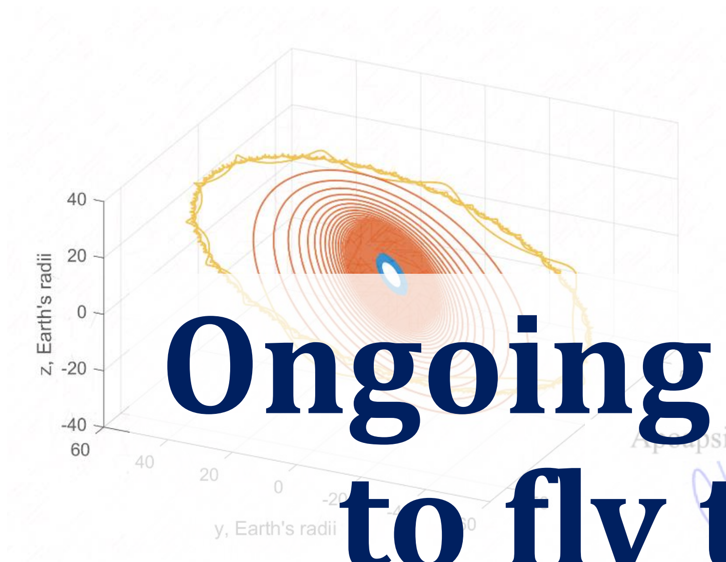
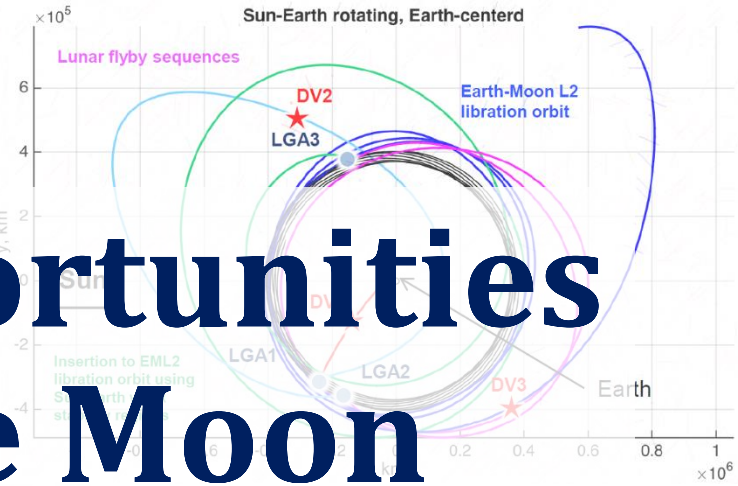
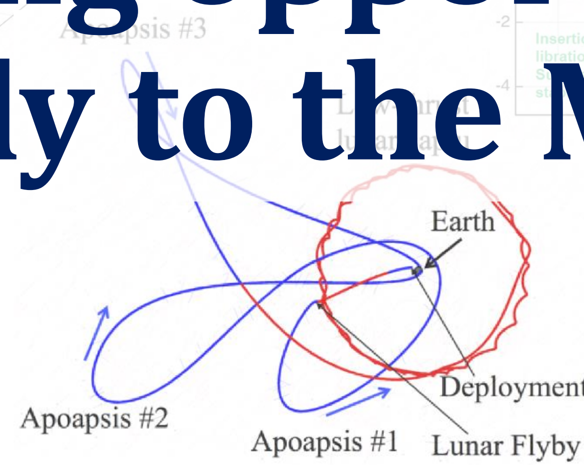
4th IAA Latin American CubeSat Workshop





Ongoing opportunities to fly to the Moon



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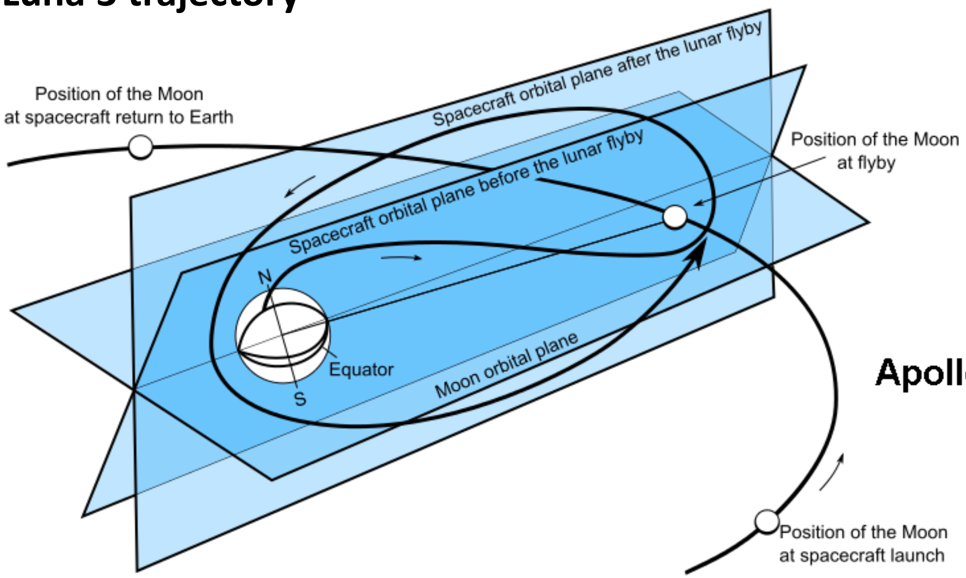
Motivation

Staff of the Space Systems Dynamics Department at KIAM

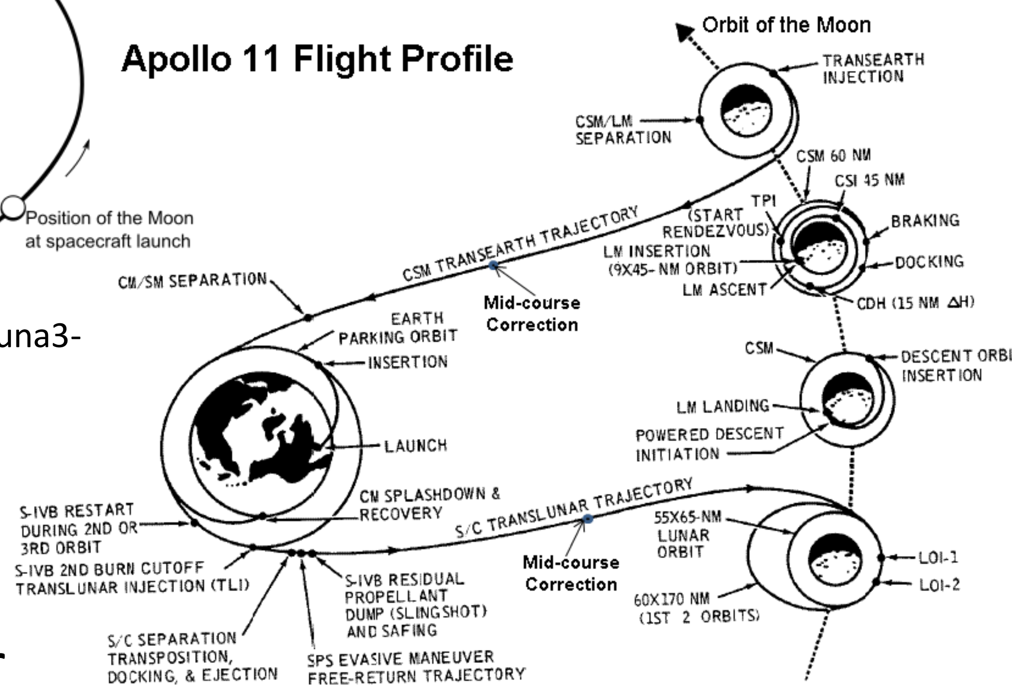
On the shoulders of giants

Luna 3 trajectory



Credit: https://commons.wikimedia.org/wiki/File:Luna3-trajectory-eng.svg

Luna 3 (1959) is the first minispacecraft (~279 kg) which flew by the Moon in a free-return trajectory



Credit: https://www.mpoweruk.com/Apollo_Moon_Shot.htm

To get to a lunar orbit, large space probes (e.g., Apollo 11) have to perform a high ΔV lunar orbit insertion (LOI) maneuver

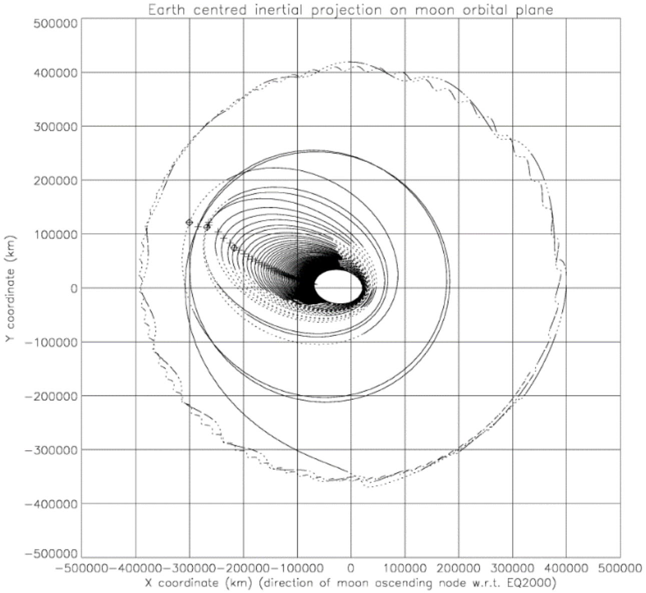
Two routes to the Moon

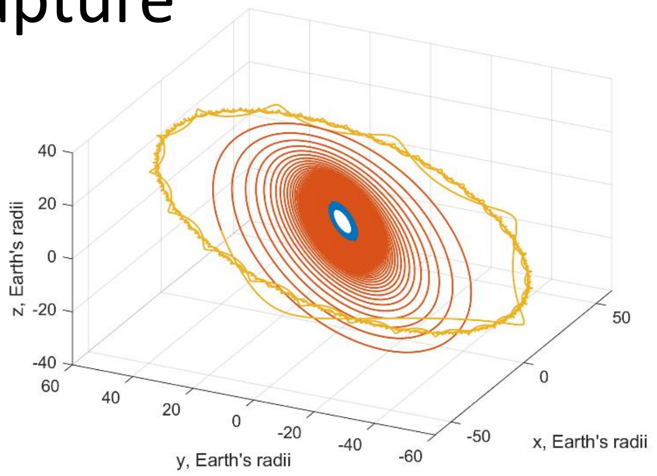
CubeSats and other nano/microspacecraft have two options to get to the Moon:

- ➢ Low-thrust transfer from a near-Earth orbit (GTO, MEO, or even LEO)
  - No spacecraft of a nano or micro class has been launched yet (SMART-1, launched in 2003, had a mass of 300+ kg)
- ➢ Piggyback launch with a large mission
  - Artemis 1 (Orion + 13 CubeSats, including Lunar IceCube, Lunar Flashlight, EQUULEUS, Near-Earth Asteroid Scout etc.)

Low-thrust spiraling

- A spacecraft is ejected into the parking orbit (GTO or MEO is usually considered), then it starts spiraling, raises the orbit above the radiation belts, and continues thrusting till the lunar capture



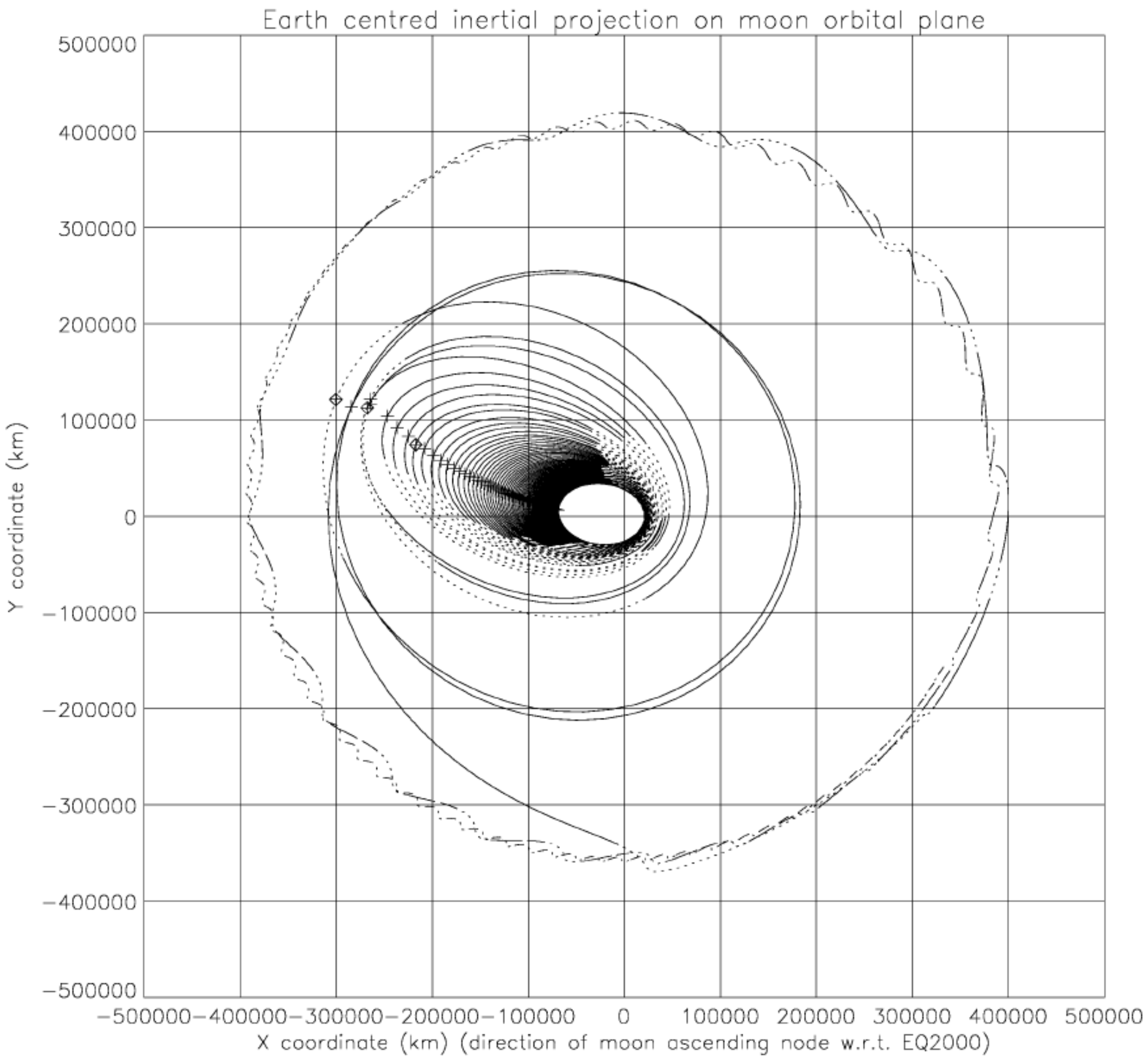


- Lunar resonant encounters greatly assist in the perigee raising process

Pros and cons of spiraling

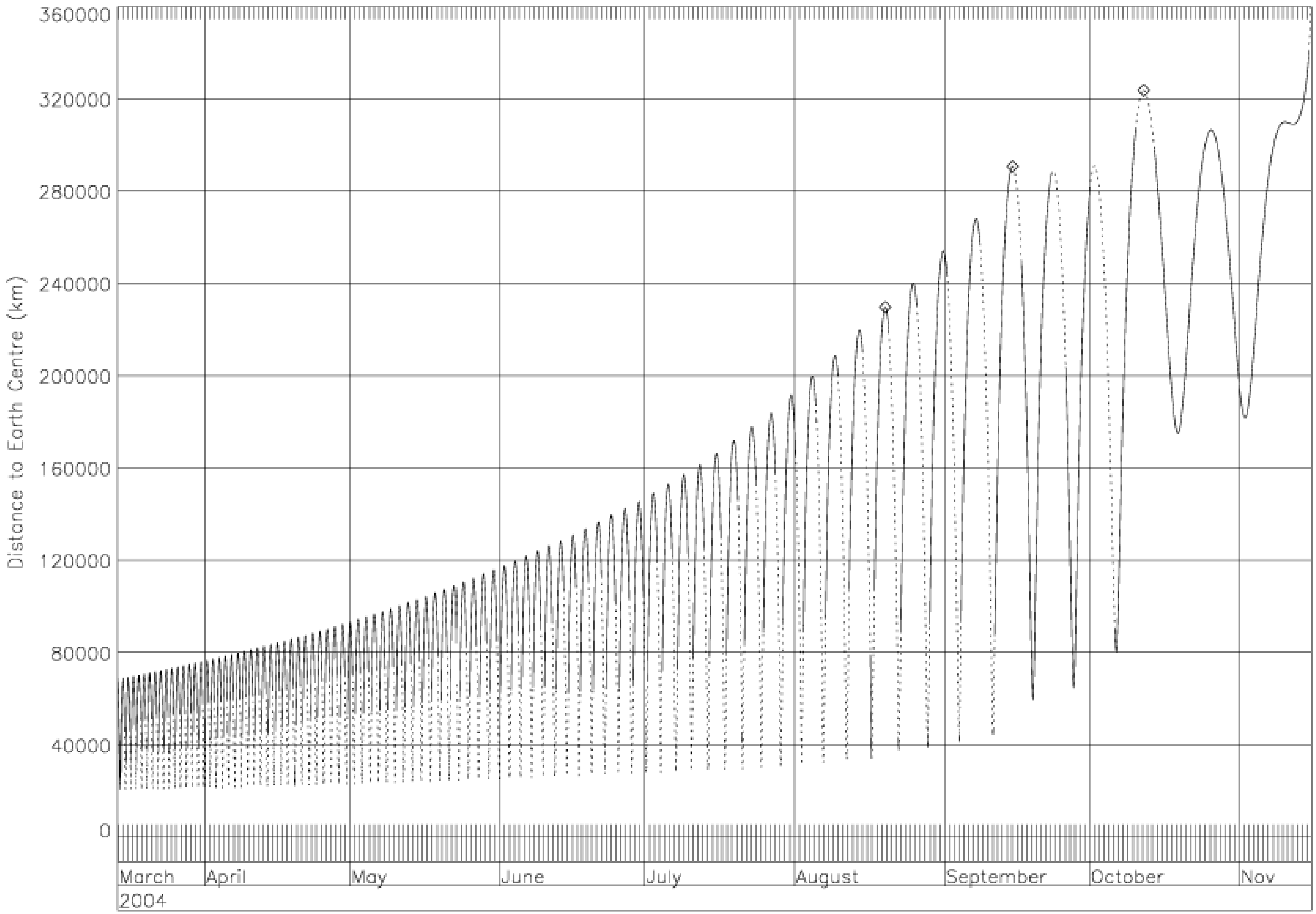
+ Launch opportunities are relatively frequent: there are a lot of GTO and MEO missions; many of them offer a secondary payload to be installed on board
– Long thrusting arcs require both sophisticated pre-launch optimization and challenging post-launch operations (high accuracy of attitude stabilization, regular control updates etc.)
– Extensive spacecraft bus shielding and/or expensive radiation-tolerant electronics (up to 50 krad or even higher) required
– Very long transfer times (about 1.5 years)

SMART-1 low-thrust transfer



Credit: J. Schoenmaekers (ESA)

Lunar resonances and capture



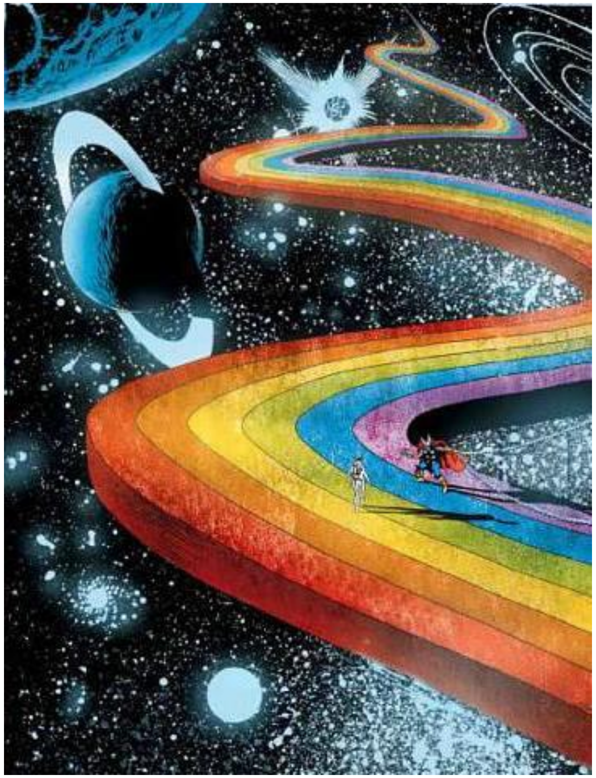
Credit: J. Schoenmaekers (ESA)

Bifrost: bridge to the Moon

The mission is a complex measurement campaign for the lunar environment (it is still basically untouched, but massive lunar exploration is about to come).

Scientific payload instruments:

- Energetic Neutral Atom detector
- Ion analyzer
- Neutral gas mass spectrometer
- FIR (H2O absorption line) imager/spectrometer
- Wide angle camera for context imaging and transient monitoring



Bifrost in Norse mythology is a burning rainbow bridge that connects Midgard (Earth) and Asgard (the realm of the gods)

More challenging than SMART-1

The mission scenario is somewhat similar to the one of SMART-1, but important differences exist:

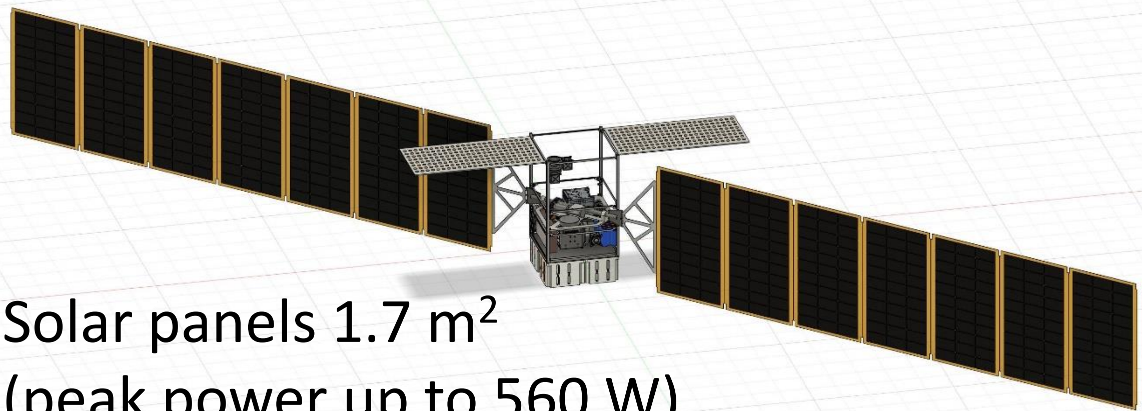
- Microspacecraft 35-37 kg, 10 times smaller than SMART-1
- Smaller thrust acceleration (0.14 mm/s^2)
- Very challenging maneuvering in low lunar orbits (LLOs): several near-polar science orbits required in the 30-100 km range
- The total amount of fuel available for the transfer and LLO maneuvering is strictly limited to 5.2 kg

Bifrost configuration

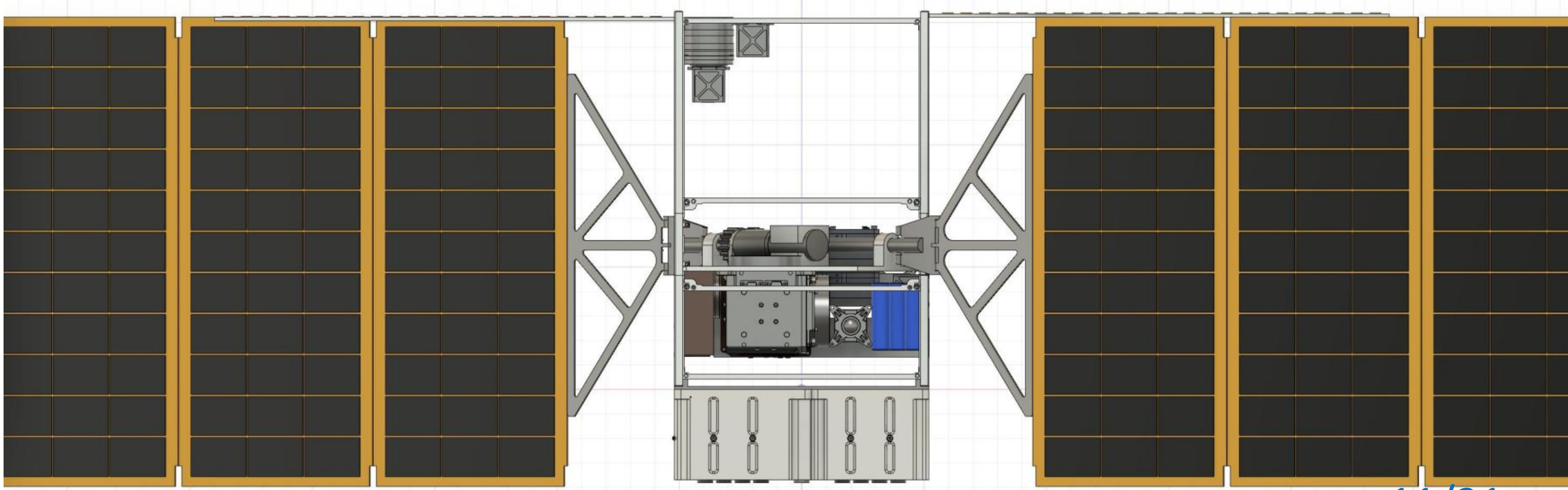
Dry mass (w/o payload): 20-23 kg

Wet mass (w/o payload): 25-28 kg

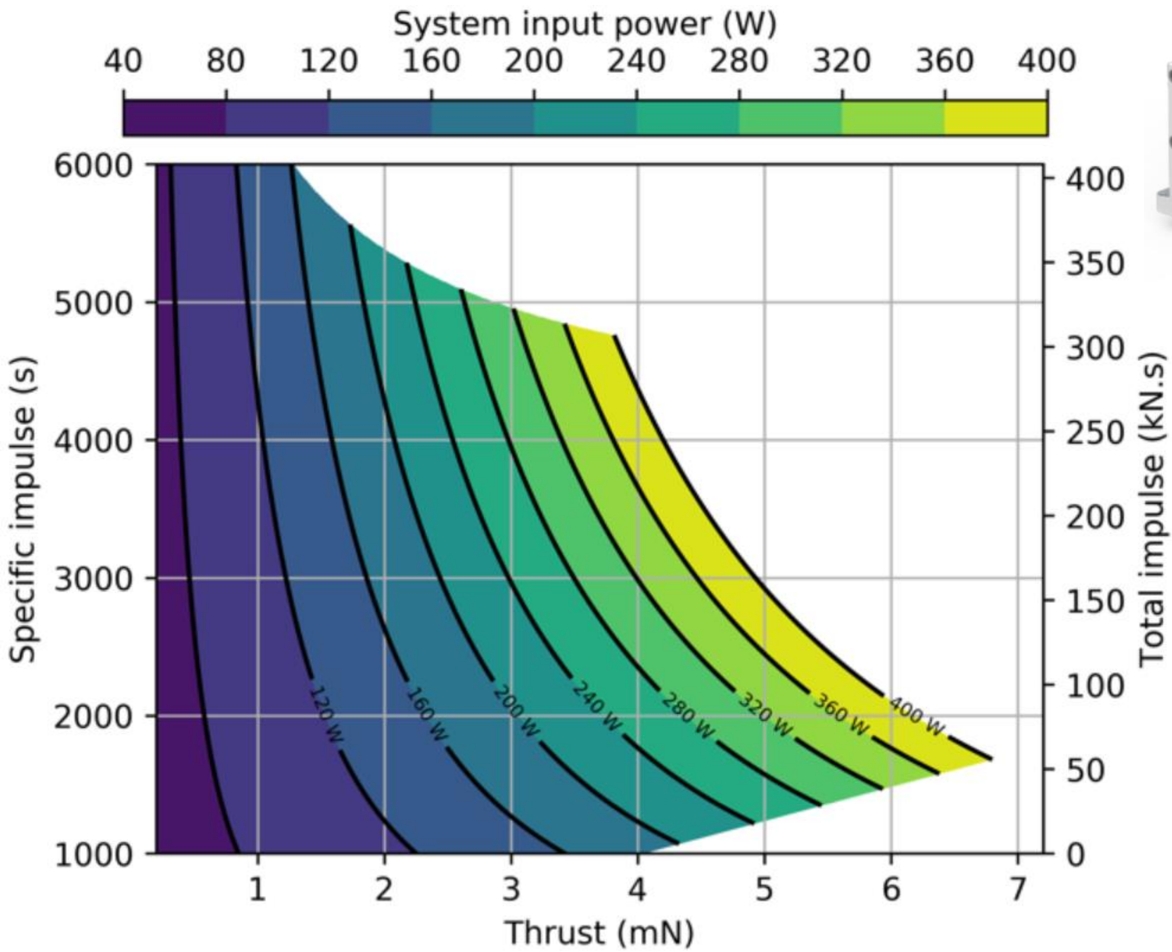
Payload: 7-10 kg



Solar panels 1.7 m^2
(peak power up to 560 W)



IFM Micro Thruster (Enpulsion GmbH)



Credit: Enpulsion GmbH

Radiation analysis of Kourou and Xichang launch options

Admissible total ionizing dose (TID) is 50 krad.

Shielding area is more than 5000 cm^2.

Radiation analysis tool: https://www.spenvis.oma.be/

Kourou launch requires 4 mm of Al shielding (≈ 6 kg).

Xichang launch requires 2.5 mm of Al shielding (< 4 kg).

Modern plastics and selective shielding can save 1.5-2 kg.

	perigee altitude, km	apogee altitude, km	inclination, deg	argument of perigee, deg
GTO	250	35,950	6	178
MEO	23,200	23,200	55	not defined

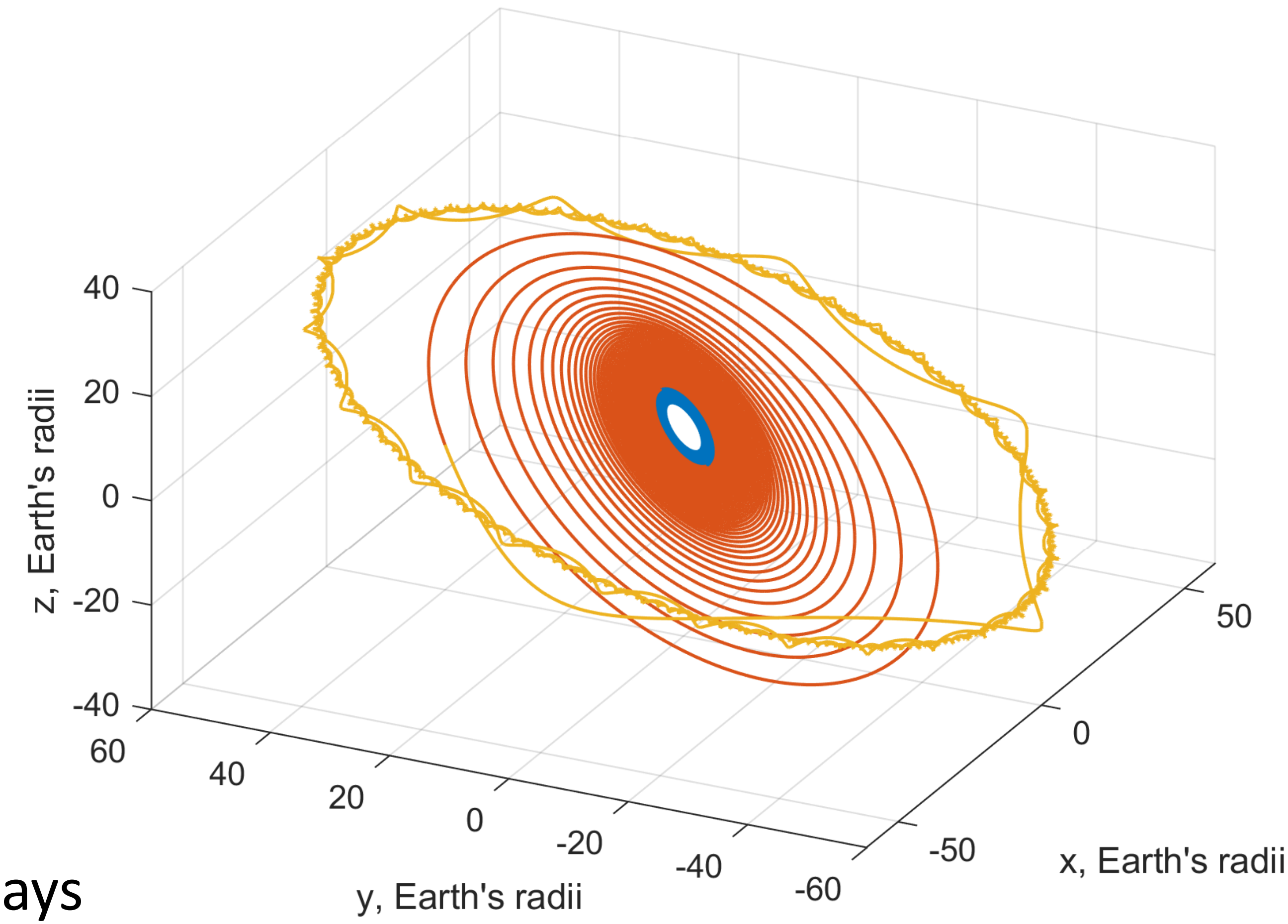
MEO-LLO transfer trajectory

MEO:
i=55 deg
h=23,200 km
e=0

Target LLO:
polar, 100 km

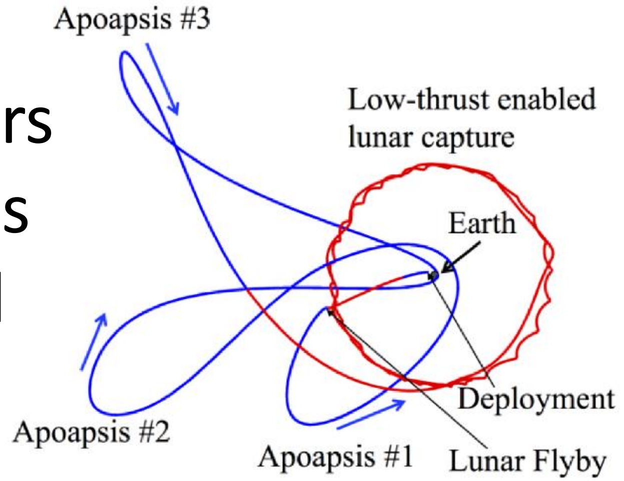
Spacecraft:
m0 = 35 kg
mf = 30.6 kg

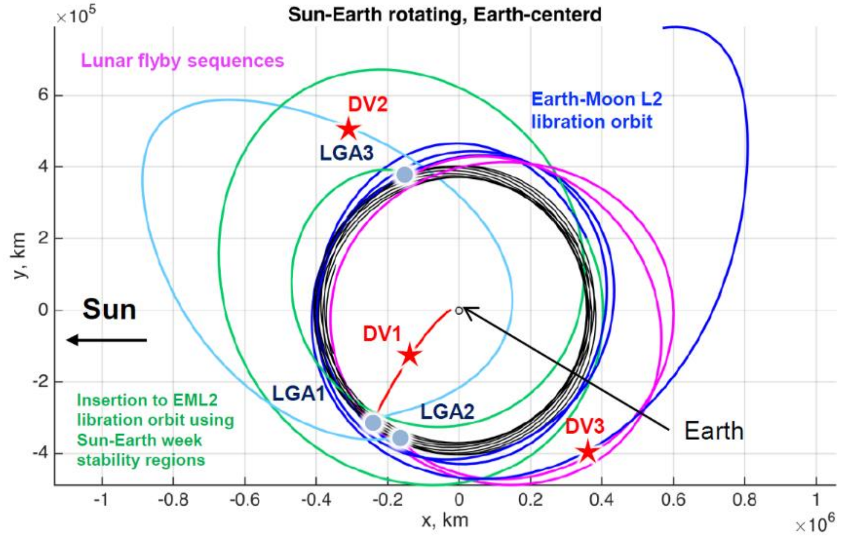
TOF (total): 443 days



Chaotic piggybacking

- Upon separation, a spacecraft adjusts the lunar fly-by parameters so that the further trajectory ends with capture into an orbit around the Moon or a libration point





- The transfer trajectory is primarily ballistic though one or several low-thrust arcs and/or lunar fly-by(s) can be included

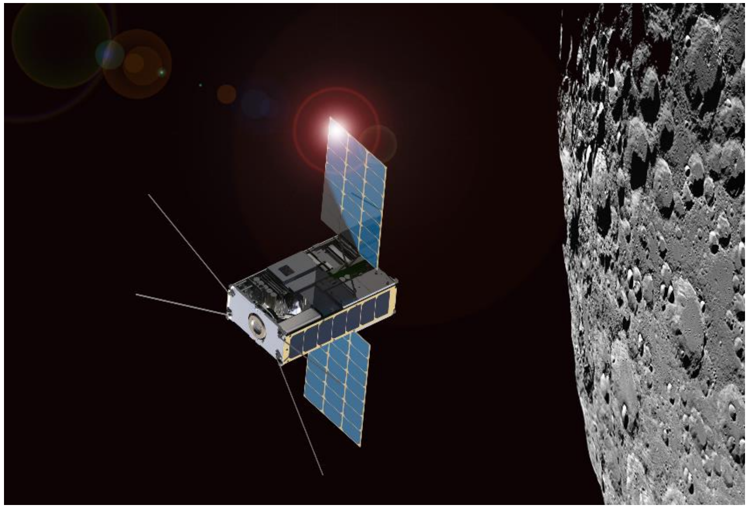
Pros and cons of piggybacking

+ Much shorter transfer in comparison with low-thrust spiraling (3-6 months vs 15-20 months)
+ Various destinations (different lunar orbits, libration point orbits) are potentially available with very low delta-v costs (tens of m/s)

– The propulsion system (a low-thrust engine or a solar sail) is required to correct the trajectory so that lunar fly-bys are properly performed
– The launch conditions are subject to unexpected last-minute changes one cannot control for

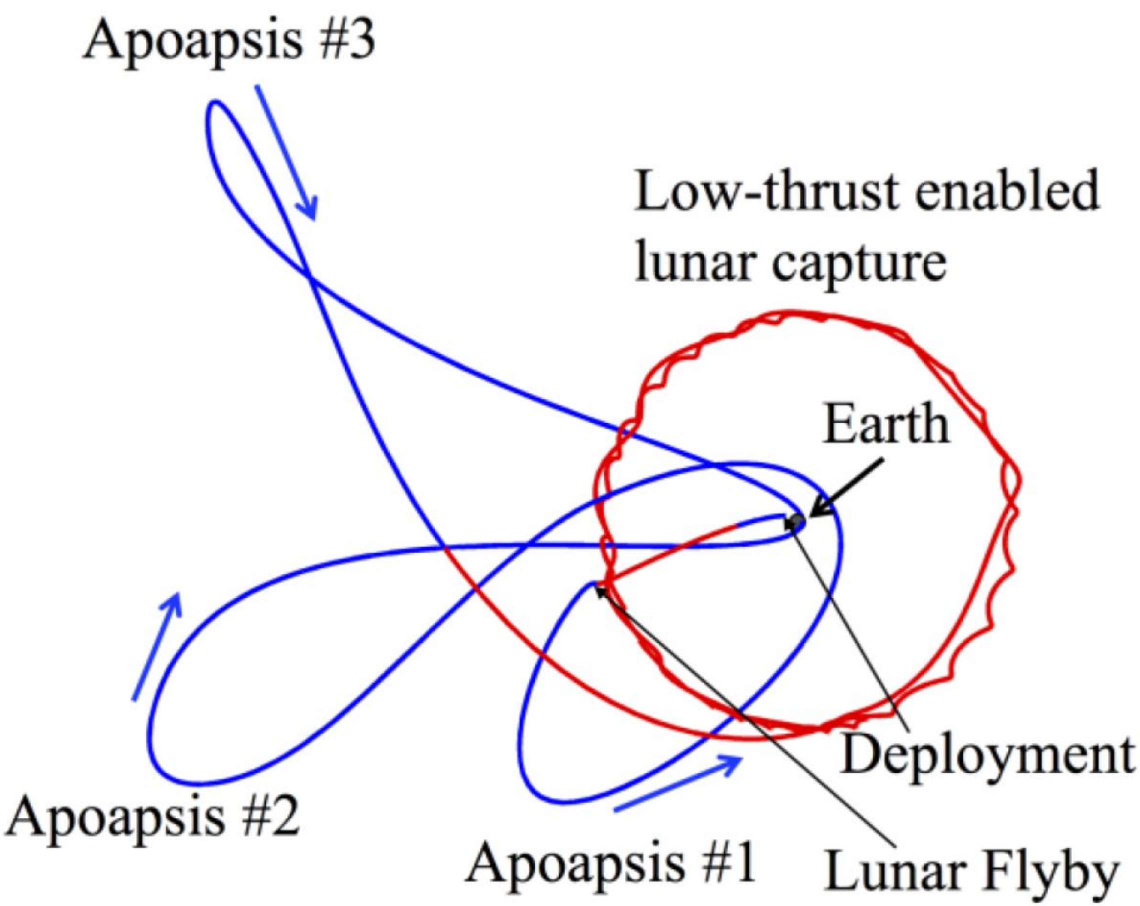
Lunar IceCube (MSU/NASA)

- 6U CubeSat 14 kg
- Primary science goal: investigation of lunar water ice deposits, water vapor and other volatiles
- Target orbit: 100x5000 km, inclination ~90 deg
- Propulsion: BIT-3 (Busek)
  T = 1.24 mN, Isp = 2250 s,
  P = 70 W, volume 1.6U
- Led by Space Science Center at Morehead State University (Kentucky, USA)



Credit: MSU, NASA

IceCube low-energy transfer



Credit: Dave Folta (NASA GSFC)

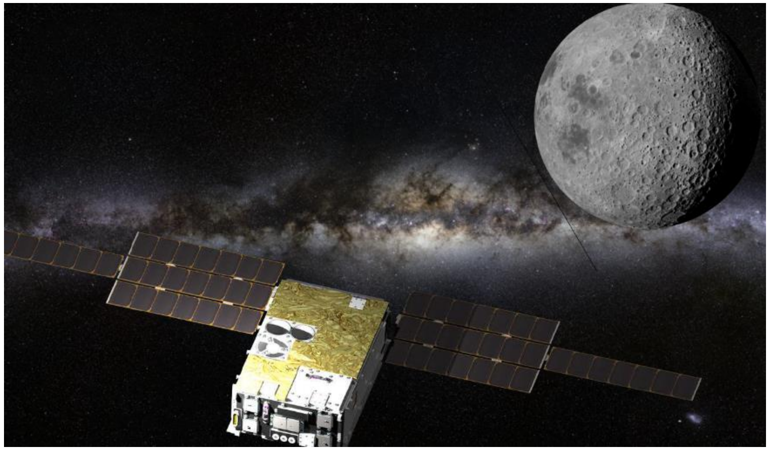
Low-thrust arcs are indicated by red. Coast arcs are blue.

The figure is plotted in the Sun-Earth rotating frame. The Sun is from the left.

The final phase of the transfer is similar to the well-known WSB Earth-Moon transfer.

EQUULEUS (UTokyo/JAXA)

- 6U CubeSat 14 kg
- Primary science goal: observation of lunar impact flashes, measurement of dust environment in the cis-lunar region
- Target orbit: Earth-Moon L2 near-rectilinear halo
- Propulsion: water resistojet T = 3.3 mN, Isp = 70 s, volume 2.5U
- Led by University of Tokyo and JAXA (Japan)



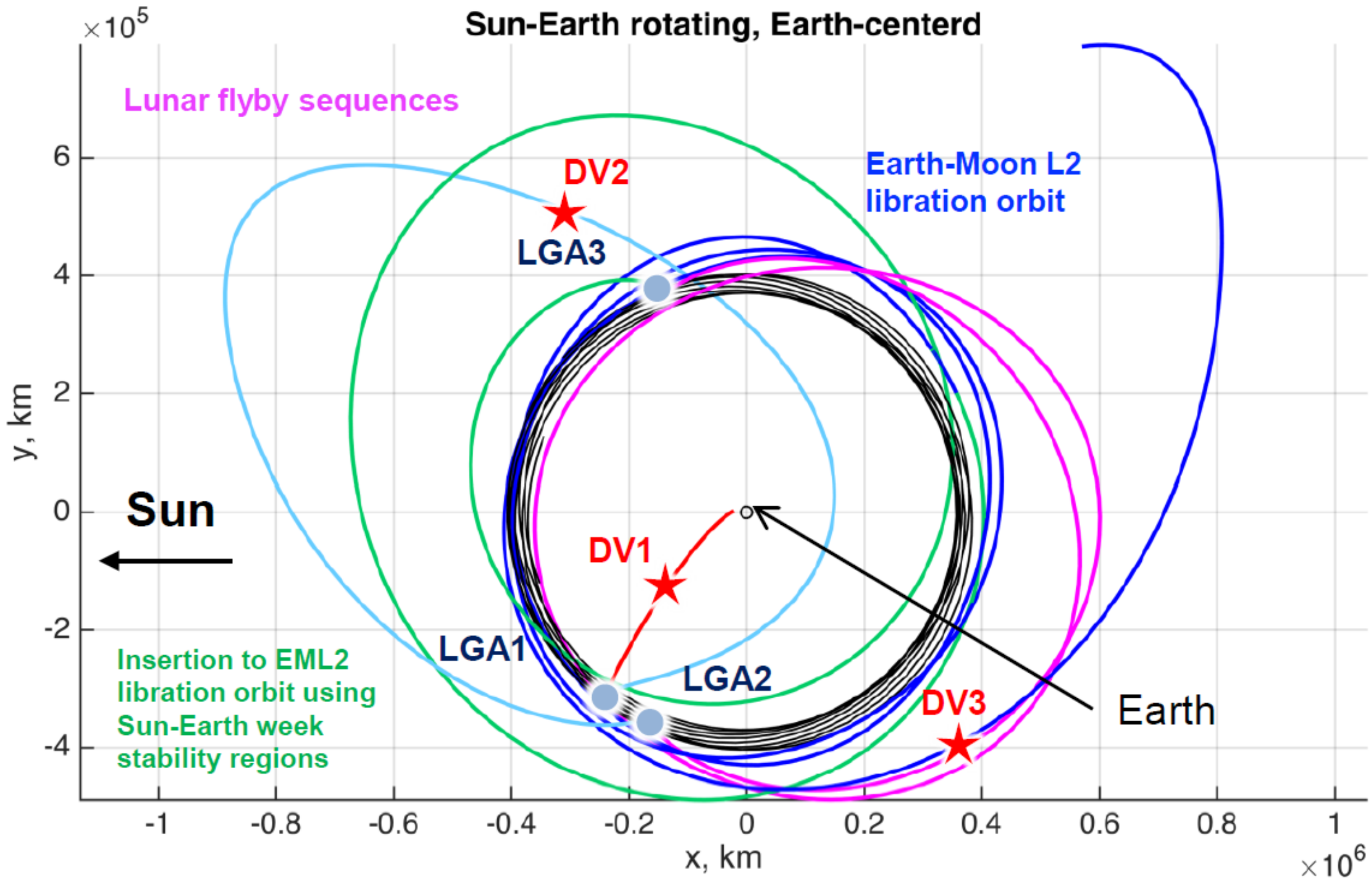
Credit: UTokyo, JAXA

EQUULEUS low-energy transfer

Time of flight: 6 months

Deterministic Δv: ~10 m/s

Number of lunar gravity assists: 3



Credit: Ruy Funase et al. (University of Tokyo, JAXA)

Conclusions

- We are on the verge of rapid growth of deep-space CubeSat/microsat missions
- Two transfer schemes – regular low-thrust spiraling and occasional piggybacking – are available
- Both are challenging from the technical viewpoint (energy, radiation, ground-link communication) and from the viewpoint of astrodynamics skills required to design a mission (low-thrust optimization, multi-body dynamics, multiple constraints)
- Deep-space CubeSat/microsat missions are attractive and effective way to involve young researchers

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