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Design and Deployment of Small Satellite Constellations Around the Moon

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New paradigm of space exploration: small satellite interplanetary missions

Rideshare launch with the InSight mission (2018)	MarCO-A/B	Mars
Rideshare launch with the DART mission (2021)	LICIACube	Didymos asteroid
Dedicated Electron/Photon launch (2022)	CAPSTONE	EM L2 halo orbit

Rideshare launch with the Artemis 1 mission (2022):

ArgoMoon	highly elliptical Earth orbit
BioSentinel	heliocentric orbit
CuSP	heliocentric orbit
LunIR	heliocentric orbit
Team Miles	heliocentric orbit
LunaH-Map	lunar orbit
Lunar IceCube	lunar orbit
OMOTENASHI	collision with the Moon
EQUULEUS	EM L2 halo orbit
NEA Scout	2020 GE asteroid

Single-spacecraft and multi-spacecraft BEO missions to the Moon and asteroids

Beyond Earth orbit (BEO) roadmap for small spacecraft:

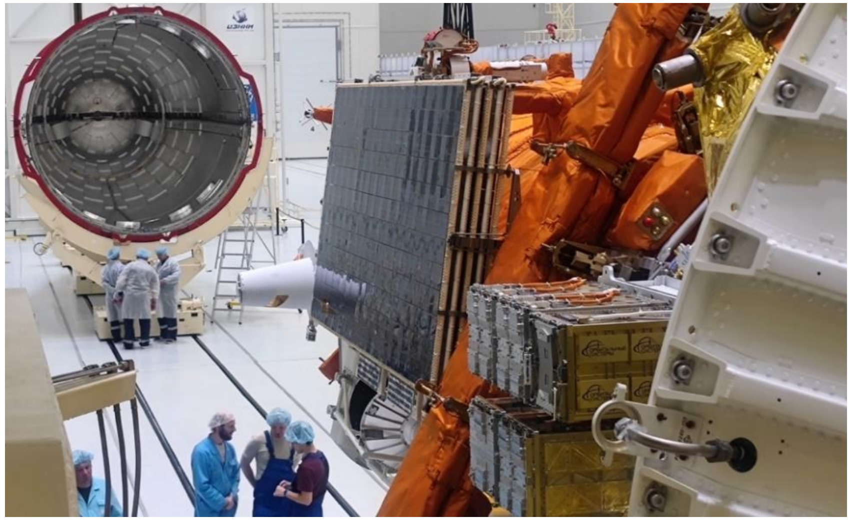
- Technology demonstration lunar mission based on 1–2 smallsats
- Deployment of a multi-plane microsatellite/CubeSat constellation for lunar communication, navigation, or remote sensing purposes
- Science mission to one of near-Earth asteroids

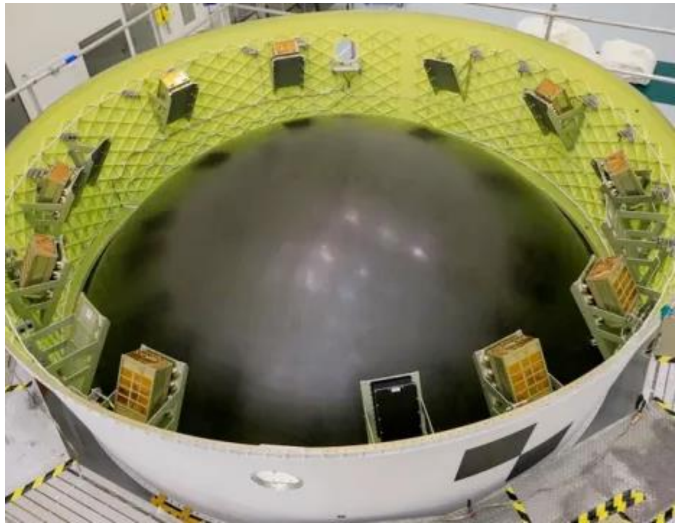
Launch scenarios for a small spacecraft mission to the Moon:

- Direct transfer with a rideshare launch
- Sun-assisted/ballistic lunar transfer with a rideshare launch
- Dedicated launch by a small-lift rocket with a small-size kick stage

Launch scheme for BEO spacecraft as a piggyback payload in LEO missions

1. The rocket delivers a stack of the kick stage and the adapter with both the primary and the secondary payload to the LEO parking orbit.
2. The former is transferred to its nominal LEO orbit and separated.
3. The kick stage provides the injection impulse for secondary small spacecraft to depart for the destination celestial body with specified C_3.





Two types of rideshare lunar transfers for smallsats and their constellations

Direct lunar transfer:

- Small spacecraft are separated from the primary payload along the fast (4–6 days) direct transfer trajectory and, without enough braking capacity, make a lunar flyby
- The following trajectory can include lunar gravity-assist maneuvers and should end with ballistic capture by the Moon into one or several weakly stable orbits

Sun-assisted/ballistic lunar transfer:

- Secondary smallsat payload is separated from the primary payload along the slow (3–6 months) ballistic transfer trajectory
- Sun's gravitational perturbation in the apogee region ensures the orbit(s) of small spacecraft evolve(s) so that the spacecraft can approach the Moon and be captured (the perigee raising and the inclination change are induced by the solar gravity)

Direct lunar transfer with a rideshare launch: EQUULEUS mission (JAXA)

Launch date: **16 November 2022**

EM L2 halo orbit insertion: **not happened (mission failed due to communication loss)**

Characteristic energy (C3): **–2.0 km²/s²**

Spacecraft mass (6U CubeSat): **10.5 kg**

Propellant available (water): **1.2 kg**

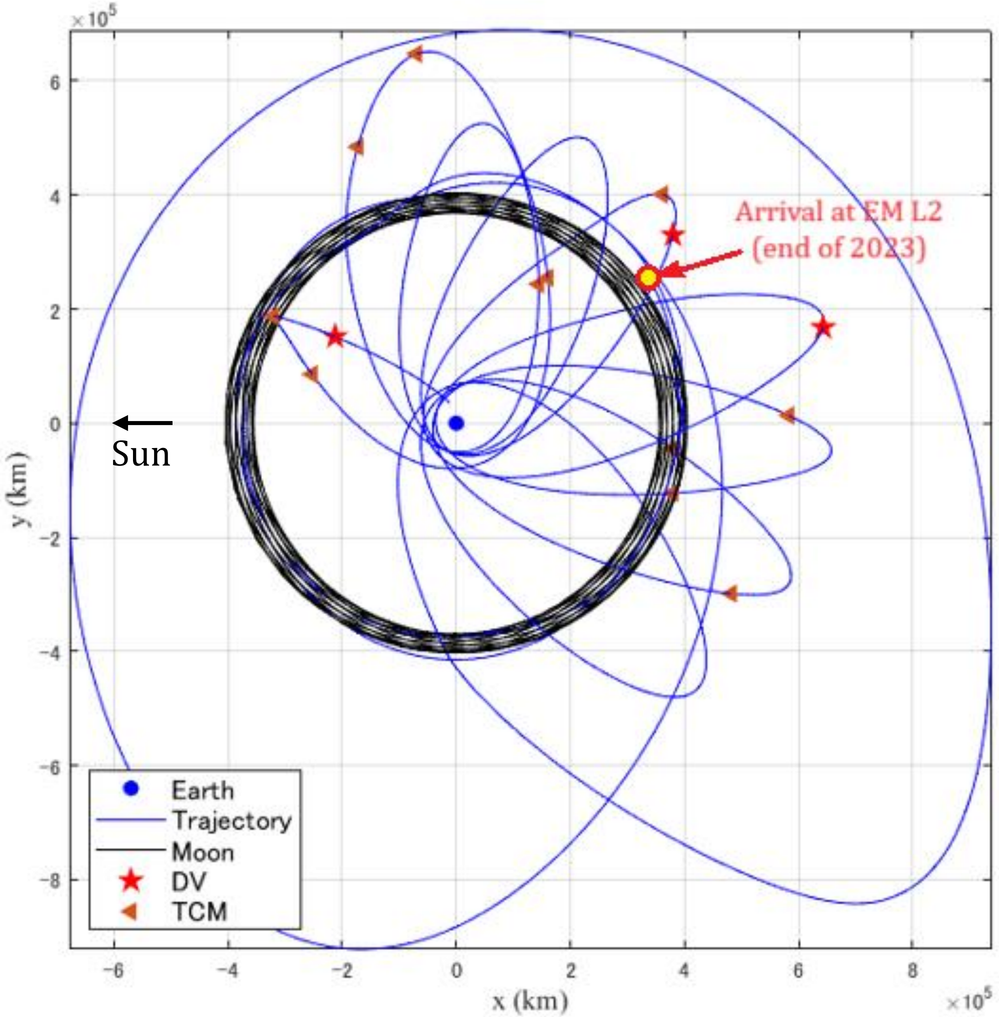
ΔV available : **80 m/s**

ΔV cost of the Earth–EM L2 transfer: **17 m/s**

Propulsion system:

2 x 2 mN for orbital maneuvering

4 x 2 mN for flywheel desaturation



EQUULEUS nominal transfer trajectory

Ballistic lunar transfer with a rideshare launch: CAPSTONE mission (NASA)

Launch date: **28 June 2022**

EM L2 halo orbit (southern NRHO 9:2) insertion: **13 November 2022**

Characteristic energy (C_3): **-0.6 km²/s²**

Spacecraft mass (12U CubeSat): **27 kg**

Propellant available (hydrazine): **3.25 kg**

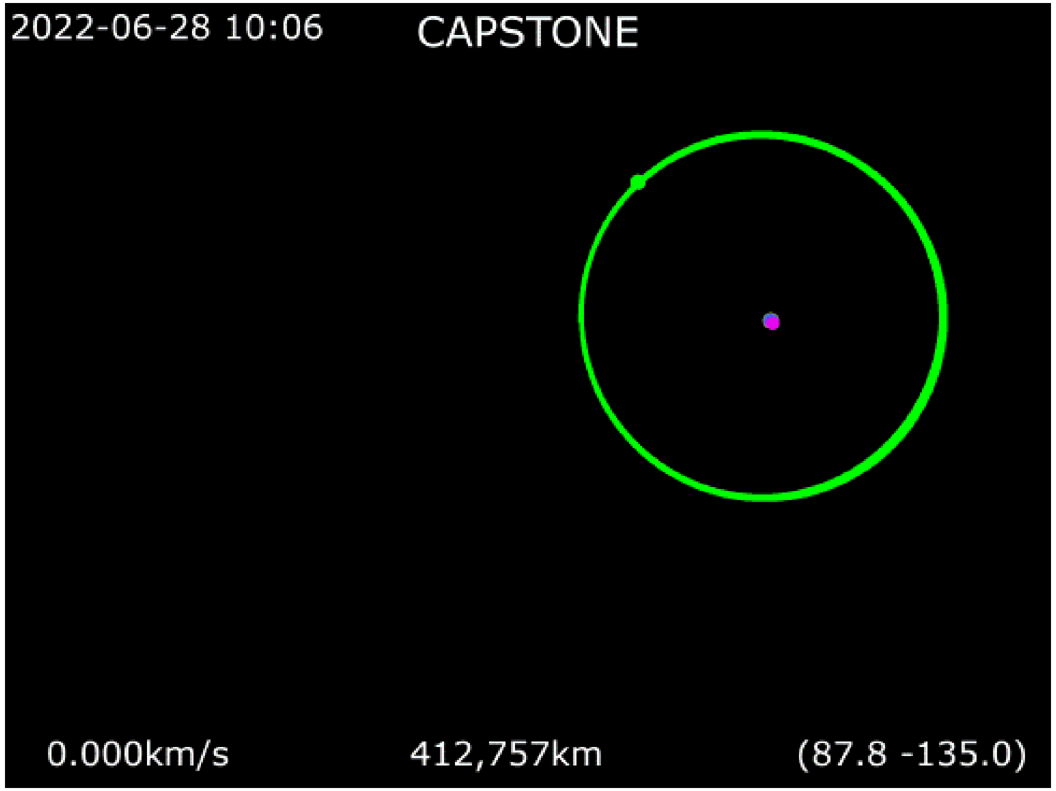
ΔV available: **240 m/s**

ΔV cost of the Earth–NRHO transfer: **94 m/s**

Propulsion system:

4 x 0.25 N for orbital maneuvering and attitude control

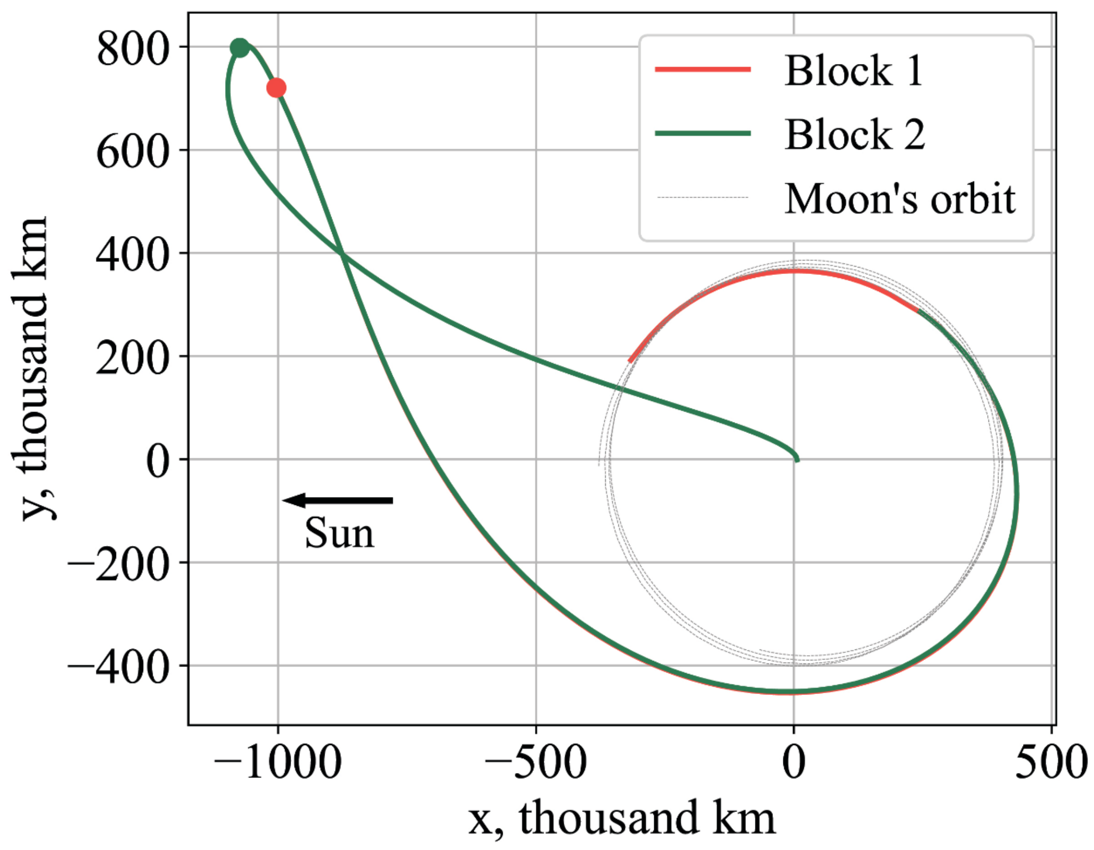
4 x 0.25 N for attitude control and flywheel desaturation



CAPSTONE nominal transfer trajectory

Single-launch deployment scheme of multi-plane lunar constellations

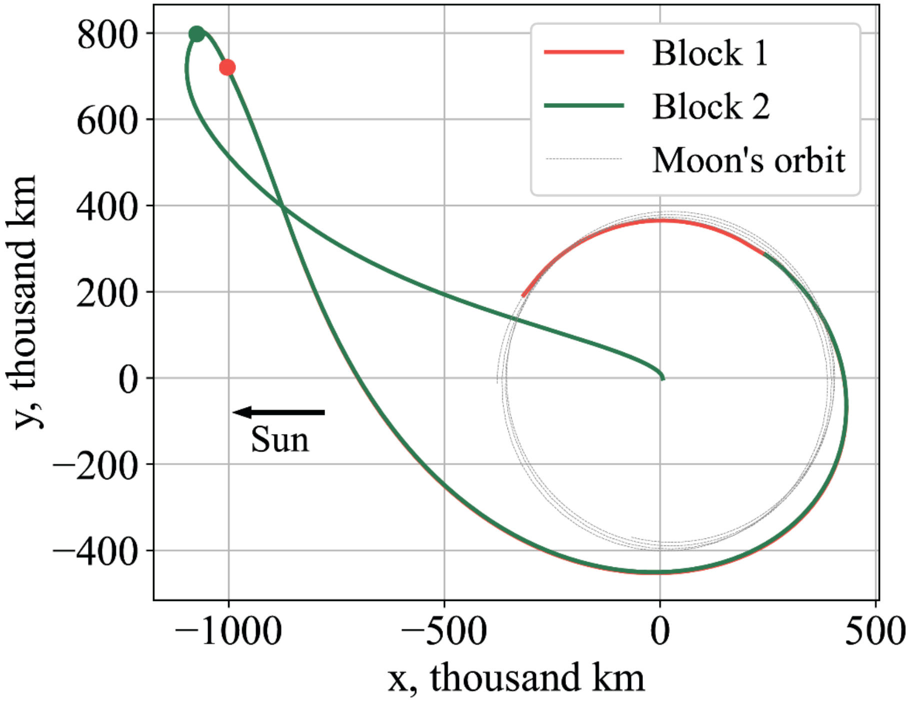
- A single platform with blocks of stacked satellites is injected from the low-Earth parking orbit into the nominal SALT/BLT trajectory
- During the transfer, the blocks of satellites are separated by a small impulse and inserted into different orbital planes around the Moon



- Upon ballistic/powered capture of the blocks into stable lunar orbits, the satellites in each block are deployed and phased along the orbit

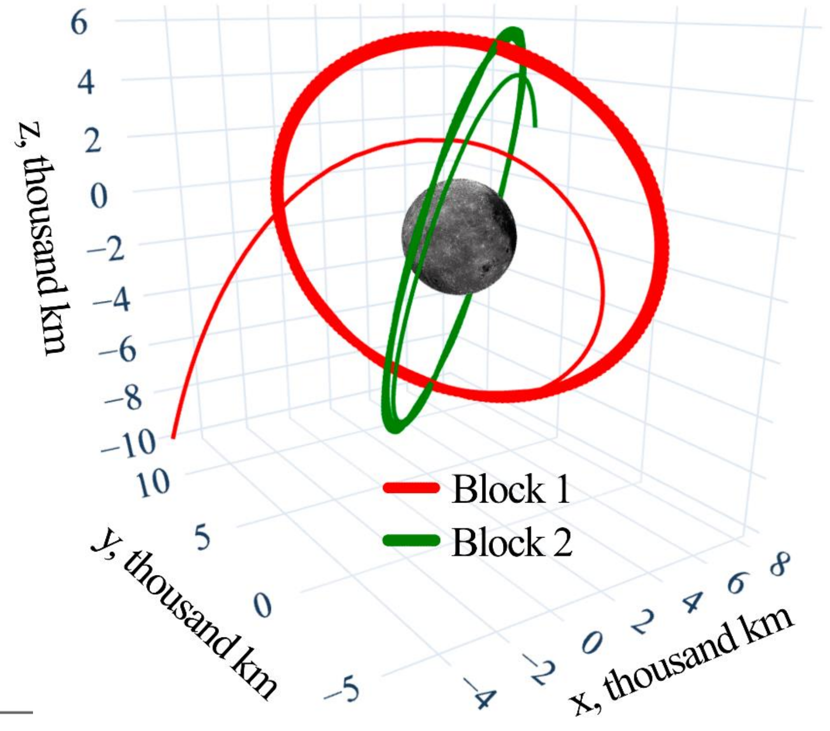
Example of low-energy deployment for a two-plane Walker constellation

The deployment cost is limited to the cost of almost coplanar transfer between the capture orbit and the nominal lunar orbit.



Orbital element	Block 1	Block 2
a, km	6200	6200
i, deg	85.7	85.6
Ω, deg	83.0	−6.7

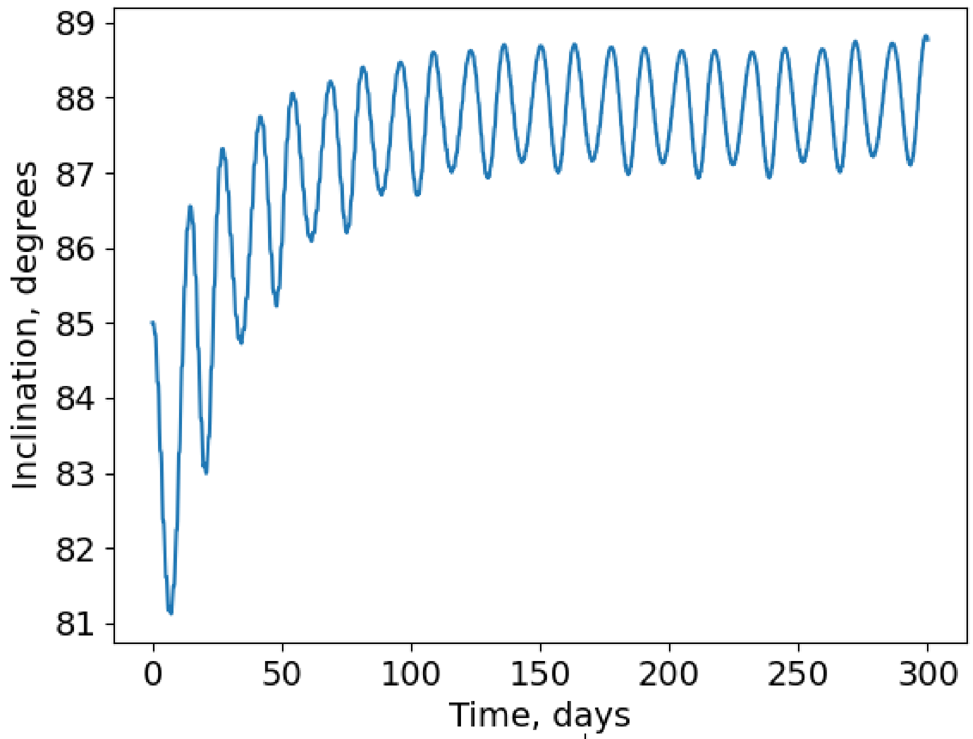
Velocity impulse	Block 1	Block 2
Δv_{dep}, m/s	2.2	1.2
Δv_{LOI}, m/s	312.0	333.6
Δv_{circ}, m/s	158.9	82.2
Δv_{tot}, m/s	473.1	417.0

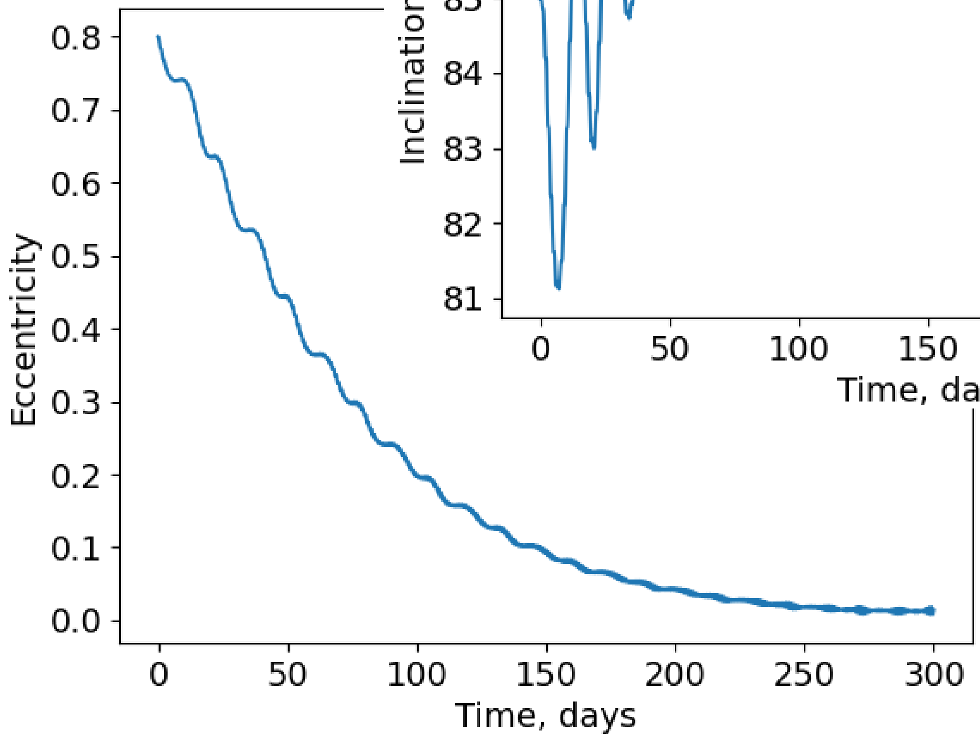


The blocks of satellites are captured by making a LOI burn at perilune followed by the circularizing burn.

Lunar ballistic capture leveraging the Oberth and Lidov–Kozai effects

- A much smaller braking impulse can be applied at a lower perilune altitude (the Oberth effect)
- The elliptic capture orbit is then naturally circularized to the nominal MLO/HLO by the Lidov–Kozai effect
- Lunar capture is up to 100% cheaper and more robust to thruster underperformance



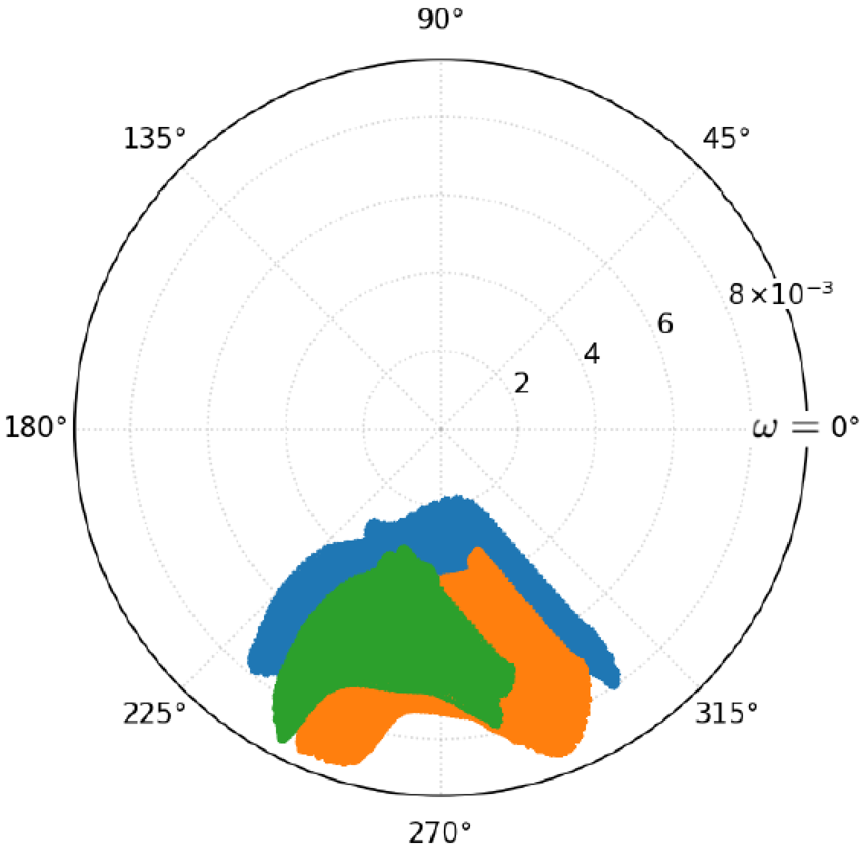


Constellations in low lunar orbits: possible if all the orbits are frozen

Examples of frozen Walker–Mozhaev lunar constellations with coverage characteristics (globally and for lunar poles)

$h_{\mathrm{ref}} = 261$ km	N_{global}	N_{North}	N_{South}	$\mathrm{PDOP}_{\mathrm{Npole}}$	$\mathrm{PDOP}_{\mathrm{Spole}}$
84°: 18/2/1 $d_{\min} = 1.01$ km	min 0 med 0	min 1 med 2	min 1 med 2	N/A	N/A
84°: 54/3/1 $d_{\min} = 0.37$ km	min 0 med 2	min 4 med 7	min 4 med 6	95% 6.5 med 2.0	95% 6.9 med 2.1
84°: 70/5/1 $d_{\min} = 0.54$ km	min 1 med 3	min 4 med 9	min 4 med 8	95% 3.2 med 1.9	95% 3.4 med 2.0
$h_{\mathrm{ref}} = 522$ km	N_{global}	N_{North}	N_{South}	$\mathrm{PDOP}_{\mathrm{Npole}}$	$\mathrm{PDOP}_{\mathrm{Spole}}$
84°: 36/3/1 $d_{\min} = 2.66$ km	min 1 med 3	min 5 med 7	min 5 med 6	95% 7.2 med 1.8	95% 7.4 med 1.8
84°: 99/3/1 $d_{\min} = 1.30$ km	min 4 med 7	min 16 med 19	min 15 med 18	95% 1.1 med 1.0	95% 1.1 med 1.0

Ovchinnikov, M., Shirobokov, M., and Trofimov, S. *Lunar Satellite Constellations in Frozen Low Orbits* // Aerospace 2024, 11, 918. DOI 10.3390/aerospace11110918



One-year eccentricity vector evolution for frozen 522 km almost polar orbits in a three-plane Walker constellation

Conclusions

- A new era of space exploration by small spacecraft is about to begin
- Smallsat constellation missions will be a natural second step in this era, as it was with near-Earth smallsat formations and constellations
- The orbit selection and the development of a constellation deployment strategy are crucial components in the design of such missions
- For lunar smallsat constellations, the single-launch deployment scheme is available when using a sensitive sun-assisted transfer trajectory
- Leveraging natural perturbations (lunar harmonics, Earth/Sun gravity) greatly improves the efficiency of constellation deployment and station-keeping for both MLO/HLO and LLO smallsat constellations