Mission Design for Deep Space Nano/Micro Spacecraft Utilizing Lunar Orbital Platform-Gateway Opportunities

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Deep Space CubeSats
Lunar Orbital Platform-Gateway (In 2020s)
LOP-G Related Launch Opportunities

Starting from NASA’s Artemis-1, we can expect **more than 10 CubeSats are launched to deep space every year.**

(Launch for LOP-G Construction, Resupply, etc…)

**Exploration Firsts**

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>&lt; 2018 Mars InSight Lander</td>
</tr>
<tr>
<td>2020</td>
<td>CLPS Small Payload Deliveries to the Moon</td>
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<tr>
<td>2020</td>
<td>MARS 2020 Mars ISRU Test</td>
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<td>2020</td>
<td>EM-1 Orion Flight</td>
</tr>
<tr>
<td>2022</td>
<td>EM-2 Crewed Mission</td>
</tr>
<tr>
<td>2022</td>
<td>GATEWAY PPE Gateway Element</td>
</tr>
<tr>
<td>2022</td>
<td>MID-SIZED LANDER Science &amp; Prospecting Lander</td>
</tr>
<tr>
<td>2023</td>
<td>EUROPA CLIPPER SLS Cargo</td>
</tr>
<tr>
<td>2023</td>
<td>EM-3 Block 1B Crewed Mission to Gateway</td>
</tr>
<tr>
<td>2023</td>
<td>GATEWAY LOGISTICS/ARM Deep Space Resupply</td>
</tr>
<tr>
<td>2024</td>
<td>LARGE-SIZED LANDER Human Class Demonstration</td>
</tr>
<tr>
<td>2024</td>
<td>Lunar/Mars Sample Return 2026</td>
</tr>
</tbody>
</table>

A New World Opened by LOP-G and Nano/Micro Spacecraft

Innovation in Earth satellite (Low cost, short lead time)
- Explosion in numbers
- Frequent missions
- Expansion of stakeholders (Startups, universities, etc)

Similar innovation will happen in deep space missions!!

Number of Satellite Launched For A Year

Source: SpaceWorks Enterprises, Inc.
Satellites Born From UNISEC Activities

What is Lunar Orbital Platform-Gateway (LOP-G)??

Lunar Orbital Platform-Gateway (LOP-G) is a planned space station in lunar orbit. NASA’s Artemis program plays a major role to develop the Gateway in collaboration with commercial and international partners: ESA, JAXA, CSA, Roscosmos, etc.
Where is the Gateway??

Near Rectilinear Halo Orbit

A type of Halo orbits under the Earth and Moon gravity.
Where is the Gateway??

The equilibrium point where the earth's gravity, the moon's gravity, and the centrifugal force balance each other is called the Lagrange point.
Lagrange Points

Five types of Lagrange points exist in each three-body dynamical system.

Ex) Earth-Moon L2 Lagrange point
    Sun-Earth L1 Lagrange point
Geometry of Lagrange Points

Sun-Earth line fixed rotational frame.
Geometry of Lagrange Points

Sun

Sun-Earth L1

L3

L4

L5

L1

L2

Earth-Moon

Gateway is here!!

Sun-Earth line fixed rotational frame.
Near Rectilinear Halo Orbit

P1: Earth
P2: Moon
Radius P2: 0.0045 Scaling: 1.0
JC: 3.0594349784036745

The Northern and Southern \( L_1 \) and \( L_2 \) NRHOs are periodic in the Circular Restricted 3-Body Model, and can be transitioned into quasi-periodic orbits in a higher fidelity model.

Jacobi Constant: 2.99957
Y Amplitude: 3.735951E04 km
Z Amplitude: 7.518863E04 km
Period: 0008.9130 days
Close Approach: 7.071249E05 km
Near Rectilinear Halo Orbit (NRHO)

Characteristics of NRHO
- Geometric relationship to the Earth is always the same
- Halo orbits are unstable (easility reachable/escapable) and spacecraft cannot stay in the orbits without station keeping maneuvers, but NRHO is less stable than general Halo orbits.
- Gateway will be constructed in 9:2 synodic resonant NRHO (SRHO), where the station never experiences eclipse.
- For 9:2 SRHO, the perilune altitude is 1458-1820km, and the apolune altitude is 68267-70112km.

(D.C. Davis, F.S.Khoury, et al. , AAS, 2020)
Launch Condition for Gateway Construction Opportunity

For gateway construction opportunities, the spacecraft is expected to be launched into lunar transfer trajectory (as was the case with Artemis 1).

Using lunar swing-by on this orbit, the spacecraft can fly to interplanetary space (to asteroid, Mars, ⋯), periodic orbits in Lagrange points, and so on.

Mission Utilizing Gateway Construction Opportunity

Launch & Separation

Lunar transfer trajectory

~1 week
Trajectory correction $\Delta V$ 
~20m/s

Lunar swing-by (V_{inf}~1km/s)

Lunar orbits, surface, Earth-Moon(EM) L1/L2, Sun-Earth(SE) L1/L2, Interplanetary (Mars, asteroids, …)

Possible mission scenario for early Artemis opportunity (such as Artemis 2)
Mission Utilizing Gateway Construction Opportunity

Launch & Separation

- Lunar transfer trajectory

- ~1 week
- Trajectory correction \( \Delta V \)
  - \( \sim 20 \text{m/s} \)

Lunar swing-by
(Vinf~1km/s)

Lunar orbits, surface, Earth-Moon(EM) L1/L2, Sun-Earth(SE) L1/L2, Interplanetary (Mars, asteroids, …)

1) To Sun-Earth L1/L2: Ballistic transfer without \( \Delta V \)

2) To Lunar Surface:

3) To Lunar orbits, Earth-Moon L1/L2:

4) To Interplanetary (Mars, asteroids):
1) Transfer to Sun-Earth L1/L2 Points

There is a manifold structure in periodic orbits around Lagrange points.

When a small $\Delta V$ disturb at each difference phase on the periodic orbit, the spacecraft leaves the periodic orbits on a group of orbits called the unstable manifold.

Because of the symmetry, the spacecraft can asymptoticaly approach a period orbit by riding on a group of orbits called the stable manifold.

(W.S., Koon, M.W., Lo, et al., AAS, 2000)
1) Transfer to Sun-Earth L1/L2 Points

By selecting a single trajectory on a stable manifold, the spacecraft can ballistically transfer to the periodic orbit around the Lagrange point.

(J.S. Parker and R.L. Anderson, JPL, p.97, 2013)
Mission Utilizing Gateway Construction Opportunity

Launch & Separation

Lunar transfer trajectory

~1 week Trajectory correction $\Delta V \sim 20m/s$

Lunar swing-by ($V_{inf} \sim 1km/s$)

Lunar orbits, surface, Earth-Moon(EM) L1/L2, Sun-Earth(SE) L1/L2, Interplanetary (Mars, asteroids, …)

1) To Sun-Earth L1/L2: Ballistic transfer without $\Delta V$

2) To Lunar Surface: Landing with 2.5km/s $\Delta V$

3) To Lunar orbits, Earth-Moon L1/L2:

4) To Interplanetary (Mars, asteroids):
2) Landing on Lunar Surface

Launch & Separation

Lunar transfer trajectory

~1 week

Trajectory correction ΔV

~20m/s

Lunar landing (V_{inf}~1km/s)

OMOTENASHI Trajectory

(S. Campagnola, et al., IEEE, 2019)

It is possible to estimate the landing ΔV by assuming a two-body problem (patched conics)

In the vicinity of the moon, vis-viva equation (orbital-energy-invariance law) gives

\[ \frac{1}{2} v^2 - \frac{GM}{r} = \frac{1}{2} v_{\infty}^2 \]

Suppose that \( v_{\infty} = 0.82 \text{km/s} \) (example of Artēmis 1) and \( r = r_M \) (lunar radius), the velocity is

\[ v = 2.514 \text{ km/s} \]

In order to land on the moon, we need to cancel this velocity, i.e., ΔV~2.5km/s.
Mission Utilizing Gateway Construction Opportunity

Launch & Separation

Lunar transfer trajectory

-1 week
Trajectory correction \( \Delta V \sim 20\text{m/s} \)

Lunar swing-by
(Vinf\sim 1\text{km/s})

Lunar orbits, surface,
Earth-Moon(EM) L1/L2,
Sun-Earth(SE) L1/L2,
Interplanetary (Mars,
asteroids, …)

1) To Sun-Earth L1/L2: Ballistic transfer without \( \Delta V \)

2) To Lunar Surface: Landing with 2.5km/s \( \Delta V \)

3) To Lunar orbits, Earth-Moon L1/L2: Direct insertion or Low-energy transfer/capture by reducing Vinf.

4) To Interplanetary (Mars, asteroids):
3) Transfer to Lunar Orbits or Earth-Moon L1/L2 points

Launch & Separation

- Lunar transfer trajectory
- ~1 week
- Trajectory correction $\Delta V \sim 20m/s$

Lunar swing-by (Vinf~1km/s)

Low-energy transfer

5 to 8 months

Low-energy capture

Direct insertion

For direct insertion, it is possible to estimate the insertion $\Delta V$ by assuming a two-body problem (patched conics). The $\Delta V$ is about 0.5-1km/s.

For low-energy transfer/capture, the solar tidal force can effectively reduce Vinf. For NRHO or other Halo orbits, only about 10m/s $\Delta V$ is required for the insertion.
3) Transfer to Lunar Orbits or Earth-Moon L1/L2 points

Launch & Separation

Lunar transfer trajectory

~1 week Trajectory correction $\Delta V$
~20 m/s

Lunar swing-by (Vinf~1 km/s)

5 to 8 months

Low-energy transfer

For low-energy transfer/capture, the solar tidal force can effectively reduce Vinf without $\Delta V$.

GRAIL (NASA) trajectory (J.S. Parker, R.L. Anderson, AAS, 2011)
Mission Utilizing Gateway Construction Opportunity

Launch & Separation

- **Lunar transfer trajectory**
  - ~1 week
  - Trajectory correction $\Delta V$
    - $\sim 20$ m/s

Lunar swing-by (Vinf $\sim 1$ km/s)

Lunar orbits, surface, Earth-Moon (EM) L1/L2, Sun-Earth (SE) L1/L2, Interplanetary (Mars, asteroids, …)

1) To Sun-Earth L1/L2: Ballistic transfer without $\Delta V$

2) To Lunar Surface: Landing with 2.5 km/s $\Delta V$

3) To Lunar orbits, Earth-Moon L1/L2: Direct insertion or Low-energy transfer/capture by reducing Vinf.

4) To Interplanetary (Mars, asteroids): Escaping by leveraging Vinf.
4) To Interplanetary Space (Mars, etc)

Exploiting solar gravity (tidal forces) can increase the Vinf with respect to the moon!!

In this case, the maximum Vinf w.r.t. the Earth is about 1.5km/s.

The interplanetary trajectory can be design under two-body problem (patched conics) with Vinf<1.5km/s.
4) To Interplanetary Space (Mars, etc)

Launch & Separation

Lunar transfer trajectory

~1 week
Trajectory correction $\Delta V$

Lunar swing-by (V_{\infty}\sim1\text{km/s})

5 to 8 months

V_{\infty}$ leveraging by solar tidal force

Lunar swing-by (V_{\infty}\sim2.5\text{km/s})

Escape from Earth

Reachable Planet for each Earth departure V_{\infty}
(under Hohmann transfer assumption)

<table>
<thead>
<tr>
<th>Planet</th>
<th>Earth departure V_{\infty}, km/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>7.53</td>
</tr>
<tr>
<td>Venus</td>
<td>2.50</td>
</tr>
<tr>
<td>Asteroid</td>
<td>Depending on the body</td>
</tr>
<tr>
<td>Mars</td>
<td>2.94</td>
</tr>
<tr>
<td>Jupiter</td>
<td>8.49</td>
</tr>
<tr>
<td>Saturn</td>
<td>10.29</td>
</tr>
</tbody>
</table>

We cannot reach most of them with $V_{\infty}=1.5\text{km/s}$
4) To Interplanetary Space (Mars, etc)

V-infinity leveraging transfer (or ΔVEGA/EDVEGA) can effectively increase the Earth departure Vinf.

If we want to increase Vinf from 1.5km/s to 3.0km/s (reachable to Mars), we need 0.83km/s ΔV (about half of Vinf increment)
Gateway Metro Map

- **Earth**
  - **ΔV~10m/s**  
    - 0.5~1yr
  - **ΔV~10m/s**  
    - 0.5~1yr
  - **ΔV~50m/s**  
    - <1week

- **Lunar Transfer Orbit**
  - **ΔV~10m/s**  
    - Several months

- **Gateway (L2 NRHO)**
  - **ΔV~500m/s**

- **Interplanetary**
  - **ΔV~10m/s**  
    - 0.5~1yr
  - **ΔV~800m/s**  
    - ~2yr

- **Sun-Earth L1/L2**
  - Ballistic, 0.5~1yr

- **L1**
  - **ΔV~10m/s**

- **Low-Lunar Orbit**
  - **ΔV~1500m/s**

- **Lunar Surface**
  - **ΔV~500m/s**

※Note: This number does not include Mars orbit insertion ΔV
**Possible Small Sat Mission Utilizing LOP-G**

When we assume that we can deliver 6U CubeSat to LOP-G (or SLS/Artemis-1 like trajectory), the following missions are possible.

<table>
<thead>
<tr>
<th>Target</th>
<th>Possible Using Current Technology</th>
<th>Challenging, Could Be Possible in the Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moon</td>
<td>Moon orbiter</td>
<td>(Soft?) Landing</td>
</tr>
<tr>
<td>Asteroid</td>
<td>Flyby to NEAs</td>
<td>Rendezvous to NEAs, Exploration to main belt asteroids</td>
</tr>
<tr>
<td>Lagrange Points</td>
<td>Earth-Moon halo, Sun-Earth halo</td>
<td>_</td>
</tr>
<tr>
<td>Mars, Venus</td>
<td>_</td>
<td>Flyby exploration, Orbiter? Lander?</td>
</tr>
<tr>
<td>Outer Planet</td>
<td>_</td>
<td>Dependent exploration (Stand alone mission could be possible if innovative technologies are developed)</td>
</tr>
</tbody>
</table>

**Bold: Possible missions by SLS, Artemis-2**
Summary

What is the Lunar Gateway?

Which orbit can the spacecraft transfer from lunar transfer orbit (Gateway construction opportunities)?

Which type of mission can the small spacecraft do by utilizing the Gateway opportunity.