Enhancement of GNSS in the Cislunar SSV and the Cislunar Navigation Satellite System

13th Meeting of the International Committee on Global Navigation Satellite Systems

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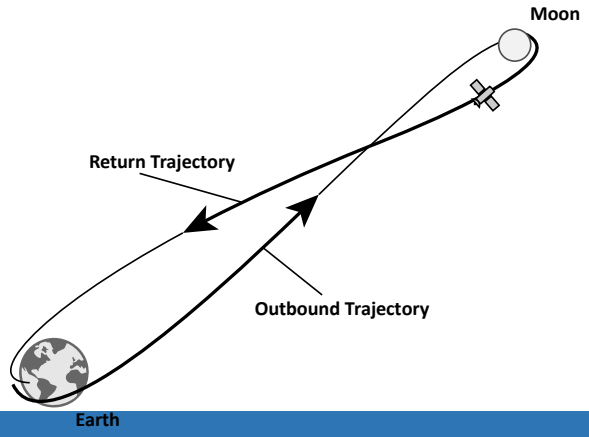
1. GNSS Performance in SSV

- The GNSS SSV is divided into 2 regions: the lower SSV, covering 3,000-8,000km, and the upper SSV, covering 8,000-36,000 km
  - ✓ In the Lower SSV: 4 or more-signals availability is 100% with combined-constellation. (Table 5.2, SSV Booklet 1.0)
  - ✓ In the Upper SSV: 4 or more-signals availability is 99.9% with combined-constellation($C/N0_{min}$=15~20 dB-Hz). (Table 5.1, SSV Booklet 1.0)

2. GNSS Performance in Cislunar Transfer Mission

- A specific mission scenario: cislunar trajectory
  - ✓ Four simultaneous signals(L5) availability is 16% with combined constellation in approximately half the distance to the Moon. (Table 5.8, SSV Booklet 1.0)
- GPS and GLONASS in Chang'E-5T lunar returning probe mission: 2 arc, both from Earth to 60,000 km.
  - ✓ The average of PDOP for only GPS is 10.1, GPS + Glonass is 8.6. (Orbit improvement for Chang'E-5T lunar returning probe with GNSS technique, Adv. in Space Research 56(2015),2473-2482)



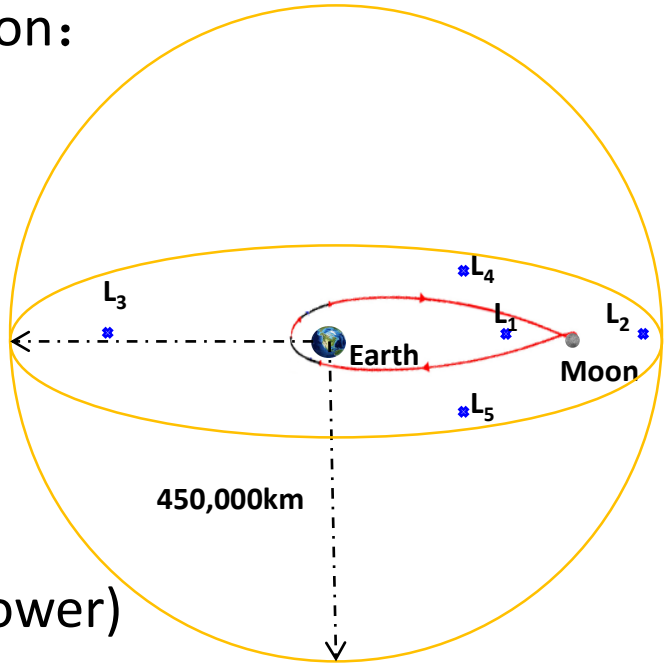
3.Missions in Cislunar Space

- The Moon is the closest natural celestial body to the Earth, and world's main space agencies have plans for further development and utilization.
- China has launched 4 lunar probes and one relay satellite since Chang'E-1 in 2007, and plans to carry out manned lunar landing and long-term lunar presence (i.e. 'Probe – Board - Stay').
- With the continuous development of space technology, the increasingly crowded near-Earth space and the increasing number of Cislunar space exploration missions, it is necessary to study the navigation service mode and system configuration of Cislunar space.

4. Augmentation of GNSS in the Cislunar SSV

- The **Cislunar SSV** - 36,000 up to 450,000 km (libration point L_2 included)

- Main consideration of Cislunar SSV application：
  - ✓ Simple user receiver algorithms
  - ✓ Real-time positioning and timing service
- Main characteristics of Cislunar SSV:
  - A. Signal visibility (i.e. 4 or more signal simultaneously , good DOP)
  - B. Signal availability (i.e. sufficient signal power)
  - C. Interoperability and Compatibility with GNSSs



5. Navigation Method for Near-Lunar Mission

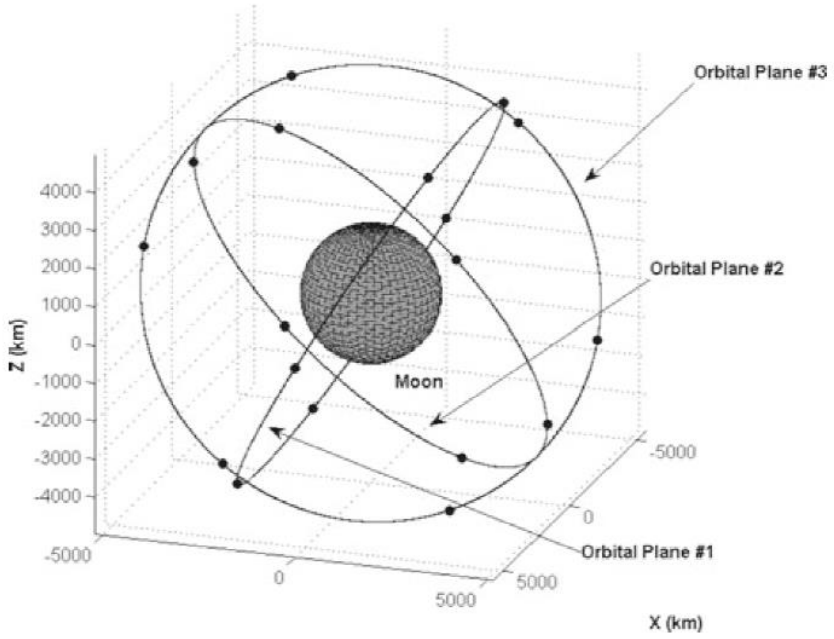
The navigation request for near-Lunar mission：

1	Near-Lunar orbit	Lunar orbiting satellite and Cislunar transfer trajectory
2	Lunar polar region	Lunar polar probe
3	Far side of the Moon	Lunar science probe
4	surface on the Moon	Man and rover activities

5. Navigation Method for Near-Lunar Mission

The Lunar Walker constellation:

- ✓ Total 18 satellites
- ✓ 3 orbit planes
- ✓ Circular Lunar orbit
- ✓ Inclination 60°
- ✓ Semi-axis 4,000km

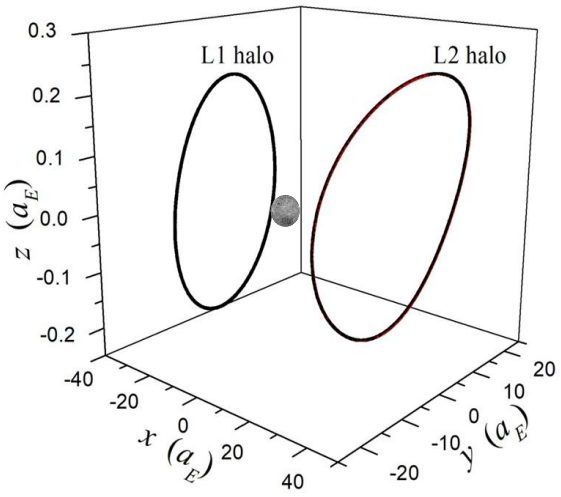


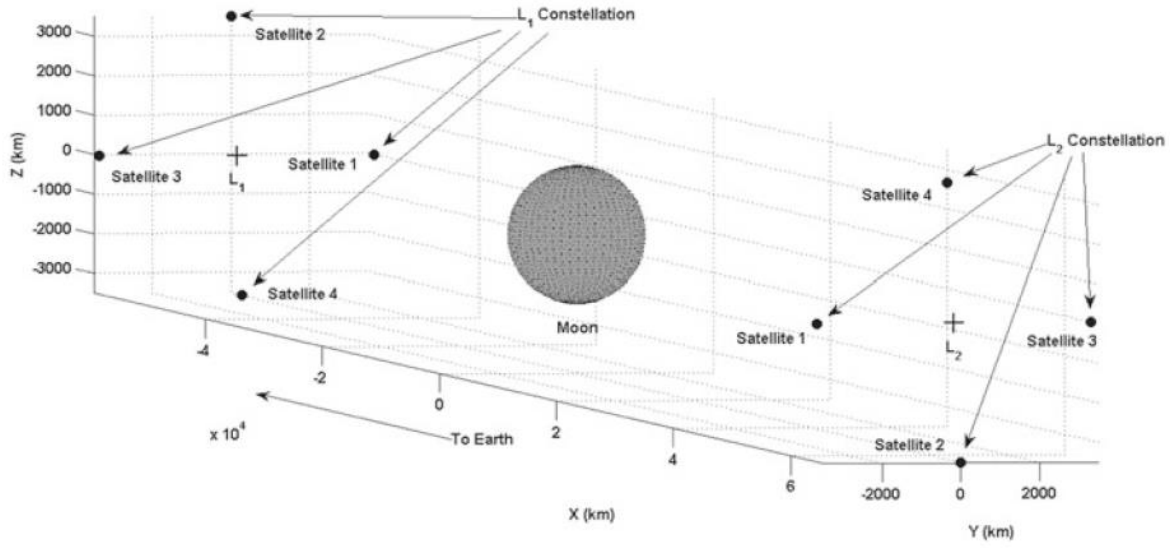
From: Romagnoli D., Circi C., Lissajous trajectories for lunar global positioning and communication systems, Celestial Mechanics and Dynamical Astronomy, 2010, 107, 409-425

5. Navigation Method for Near-Lunar Mission

Satellites around the Cislunar libration point L1&L2:

- ✓ 4 satellites around each libration point, total 8 satellites.
- ✓ Covering full surface of the moon(considering lunar libration motion), with 97.7% coverage at a certain time slot.





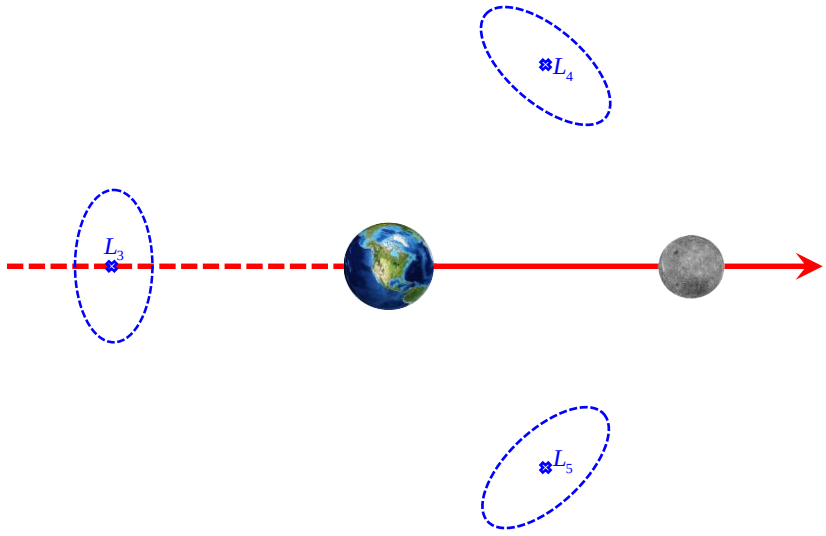
6. Navigation Method for Cislunar Space Mission

The navigation request for Cislunar space mission：

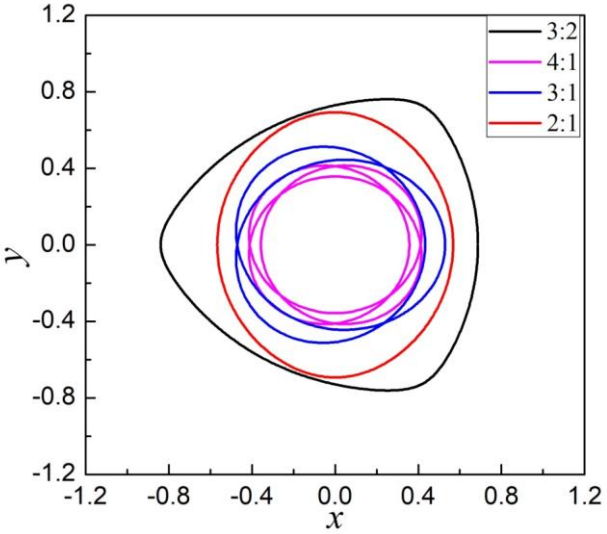
- ✓ Navigation for communication satellites near Cislunar liberation point L3/L4/L5 (Lee. Communications satellite system by using moon orbit satellite constellation, Journal of Astronomy and Space Sciences(2003), 20:313~318)
- ✓ Navigation for Cislunar communication relay satellites (A.Hornig, Demonstrator and operational satellite mission Earth-moon-libration point EML-4 for communication relay provision as a service. Acta astronautica. 2015, 108:156-170.)
- ✓ Navigation for other Cislunar scientific missions, such as environmental monitoring spacecrafts (R. W. Farquhar. The flight of ISEE-3/ICE: origins mission history, and a legacy. Journal of the Astronautical Sciences. 2001, 49(1):23-74.)

6. Navigation method for Cislunar Space Mission

- ✓ The triangular libration points in the real Cislunar system allow stable motion around them. The L3 has much better stability than the L1, L2 points.
- ✓ 3 satellites on L3, L4, L5 can constantly cover 99% of the Earth's surface.
- ✓ With a probe located at L2 point, the navigation constellation can also cover 99% of the Lunar surface.
- ✓ Observation from the L2,L3,L4,L5 constellation can compensate the observations from the Earth GNSS and the L1/L2 points. The navigation satellite can also completely cover the interplanetary transfer orbits within the Cislunar SSV.



6. Navigation Method for Cislunar Space Mission



- ✓ The libration points are actually 1:1 resonance orbits, whose orbital angular velocity is same as that of the Moon. We can extend from the libration points to other resonance orbits in the Earth-Moon orbits such as the ones shown in this picture.
- ✓ The advantage of these resonance orbits is that satellites can periodically cover the volume inside them, with a shorter communication range from the Earth than the satellites around the L3, L4, L5 points. The disadvantage is that it has coverage gaps at the Moon side if there are only a few (~3) navigation satellites on these orbits.
- ✓ Orbits inside the 2:1 resonance orbits are generally stable in the ephemeris model of the Cislunar system.

7. Concept of Cislunar Navigation Satellite System

The space segment of cislunar navigation satellite system contains 3 modules:

- ✓ **Near-Earth Module:** existing GNSS covering from the Earth surface to current SSV, i.e. -36,000 km.
- ✓ **Near-Lunar Module:** the lunar navigation satellite system covering from the Lunar surface to Cislunar L2 point.
- ✓ **Cislunar Special Orbiting Module:** the space constellations designed for covering specified or full cislunar space together with near Earth and near Lunar navigation systems

7. Concept of Cislunar Navigation Satellite System

- ✓ **The near-Earth module** consists of existing GNSS systems.

  - nearly 100% coverage to 36000km altitude with all GNSS constellation combined
  - partially support translunar, and interplanetary missions

- ✓ **The near-Lunar module** consists of navigation satellites on Lunar orbits or some special orbits such as the libration point orbits.

  - coverage from lunar surface to L1/L2 altitude
  - partially support translunar, and interplanetary missions

- ✓ **The Cislunar special orbiting module** consists of navigation satellites on L3/L4/L5 points orbit.

  - specified mission service or full coverage of cislunar space
  - satellite antenna orientation adjustment

8. Recommendation in the Cislunar SSV Research

- To study the roadmap of Cislunar Navigation Satellite System construction in accordance with cislunar space exploration and scientific research missions.
- To study the scheme of cislunar SSV constellation configuration, and optimization design including insertion cost, station-keeping cost, navigation accuracy , earth access, etc.
- To study the modification possibility of subsequent GNSS satellites e.g. a directional antenna for transmitting GNSS signals, so that the spacecraft departure from the earth can continuously obtain the navigation services for the whole journey.

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