Lunar orbit stability for Small Satellite mission design

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Agenda

1. Introduction – Small Satellite lunar missions
2. Lunar Orbits
3. Orbital element evolution and stable regions
4. Examples of maneuver and orbital maintenance applications
5. Conclusion
Small Satellite lunar missions

- **Past missions. Relatively large mass (~ 400-700 kg):** LADEE, LCROSS…
- **Future Lunar Cubesats: Lunar Flashlight (6U bus)**

- **Very limited ΔV budget once the mission achieves orbit**
  - Orbital maintenance should be ideally not required
  - Small maneuvers for corrections in order to comply with science requirements

- **Low mass and power budgets**
- **Challenge in communications**
- **Strict science requirements**

- **Propellant needed for a variety of reasons:** Avoiding interference or collision with other orbiters, End Of Life requirements …
Lunar orbits

- Lunar gravity field is extremely irregular. Orbit propagation is chaotic and unstable in most cases
- Lunar mass concentrations with high density are distributed unevenly
- **Main perturbations:**
  - Lunar mass concentrations
  - Earth/Sun third body effects
    - Main contribution over 700 km
    - Significant between 400-700 km
    - Small between 100-400 km
    - Almost negligible below 100 km
  - Solar radiation pressure

Image from 'Lunar constants and model document'. Jet Propulsion Laboratory, 2005
Orbital stability

- Over each lunar sidereal period (27.32 days), the polar plot of the eccentricity versus the argument of periapsis follows the same pattern.

- Usually, the signature in the plot moves and does not come back to the same starting point in the next period.

- Ideally, the orbital elements should not drift significantly. If this happens, a frozen orbit is found.

Bottom image from 'Lunar Frozen Orbits'. David Folta et al., 2006
Effects of initial RAAN and inclination

- Simulations carried out for two years with various RAAN/inclination configurations

- Initially circular orbits. Starting altitudes:
  - Top: 100 km
  - Middle: 150 km
  - Bottom: 200 km

- Right Ascension of the Ascending Node (RAAN) is fundamental to address stability

- A convenient configuration of RAAN/inclination can lead to a stable region where there are no collision orbits

- The effects are reduced by growing altitude. However, certain inclinations do not provide long term stable orbits at any RAAN
Lifetime

- Initially circular orbit at 100 km of altitude. Various RAAN/inclination configurations

- Even in the unstable regions, some orbits last several days

- RAAN still plays an important role, specially at higher inclinations

- Some inclinations give very limited lifetime at any possible configuration. Orbital maintenance is mandatory for these cases
Posigrade and retrograde motion

Analysis of minimum altitude of periapsis gives nearly symmetrical results with a slight difference in magnitude.

Even if the minimum altitude is similar in some cases, the average altitude values in the propagation are different. This results into a slightly different evolution over time.
Example of stable orbit

- 200 km initially circular orbit. RAAN = 0 deg. Inclination = 28 degrees

- Eccentricity does not vary by a large magnitude

- Polar plot over two years does not change significantly

- Minimum altitude of periapsis varies by less than 20% with respect to the nominal orbit altitude (~165 km)
LP150Q/GRAIL gravity models

- 15x500 km elliptical orbit. $\Omega=270$ deg. RAAN = 0 deg. Inc = 90 deg

- GRAIL used 200x200 order and degree. LP150Q used 70x70

- GRAIL has up to 660x600 order and degree
Example: stability for the DARE mission concept

- The mission required to stay in a low altitude lunar orbit for at least two years with very limited orbital maintenance

- The inclination needed to be nearly zero in order to comply with science requirements

- Results show a window of stable inclinations at any RAAN

- A threshold of 40 km of minimum perilune altitude was selected
The goal was to stay in a radio-quiet region for at least 1000 hours over two years.

Stability analysis played a key role: the orbit needed to be stable but perturbations needed to be large enough to obtain an average altitude over time that would enable the spacecraft to comply with science requirements.

Even if the retrograde cases were stable like their counterparts, the perturbations were not large enough to make the spacecraft stay within the radio-quiet zone for sufficient time.
Example: EM-1 deployment and polar frozen orbit

- Trajectory calculated with EM-1 ephemeris
- Flyby to the Moon and capture at close encounter
- Frozen orbit with argument of periapsis of 270 degrees
Example: EM-1 deployment and Reiner Gamma coverage

- Study of Lunar Swirls in Reiner-Gamma
- Passes over Reiner-Gamma location at low periapsis altitudes ~ 15 km
- ~ 3 m/s maneuvers to maintain periapsis altitude
Example: South Pole concept

- **GOAL:** maintaining a stable orbit to pass over polar latitudes without compromising the mission
- **High thrust:** 38 maneuvers over 6 months. 48 m/s in total
- **Low thrust:** 17 maneuvers (continuous burn and coast) over 6 months. 53 m/s in total
- **Altitude** was kept below 40 km at any time. Argument of periapsis did not change significantly over time
Conclusions

• Analysis performed with high-fidelity orbital propagation is a fundamental asset for future lunar missions, in particular CubeSats

• Initial orbital elements at LOI play a significant role and they need to be taken into consideration for lunar orbit mission design

• Determined set of orbital parameters define boundaries between stable and unstable orbits

• Lifetime and orbital element evolution should be calculated for any of these configurations

• Station keeping strategies can be optimized to save propellant mass
Thank you for your attention
Alternative figures
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