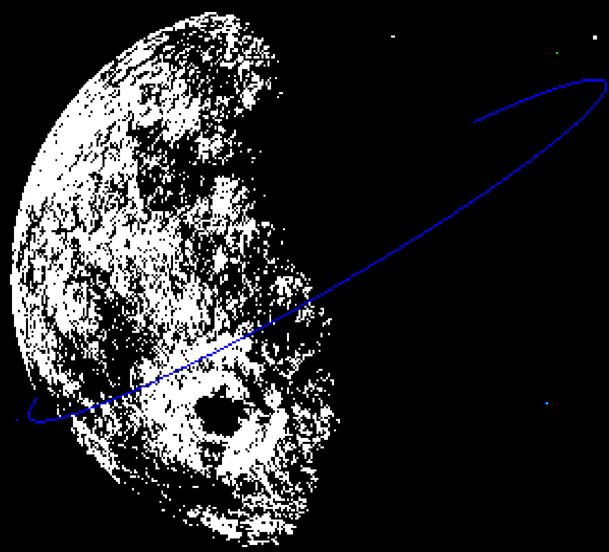
National Aeronautics and Space Administration

Ames
Discovery · Innovations · Solutions

Lunar orbit stability for Small Satellite mission design



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4th Interplanetary Cubesat Workshop
26th-27th of May 2015

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**

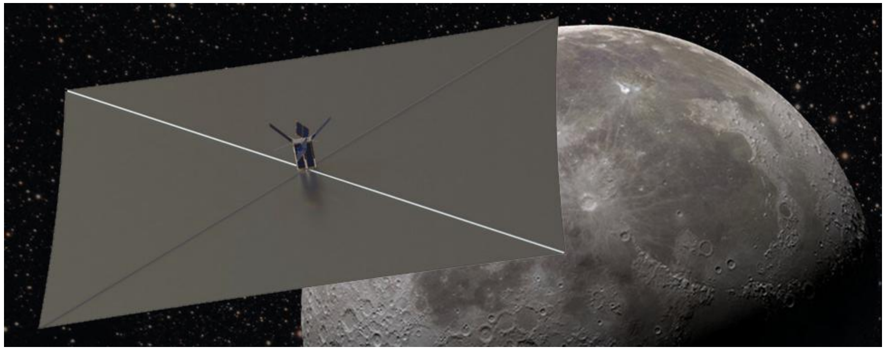


Image of Lunar Flashlight Mission, Jet Propulsion Laboratory

- **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

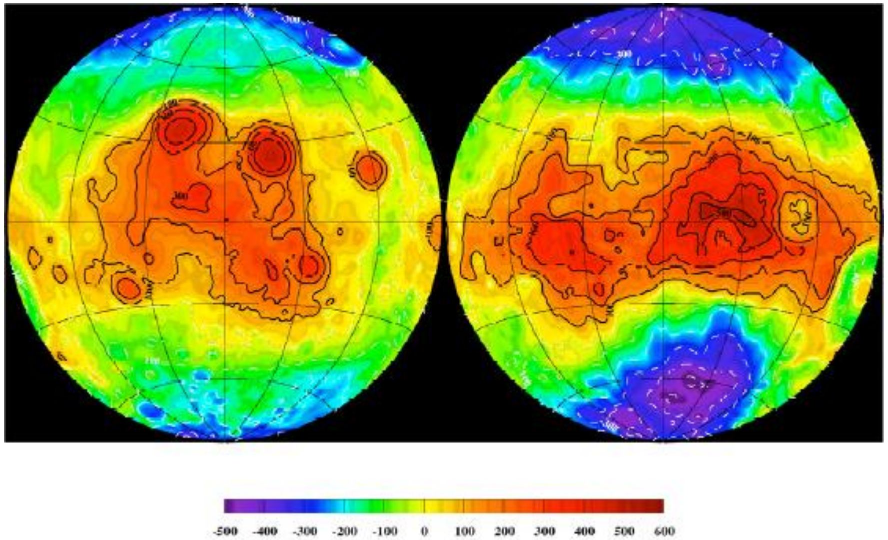
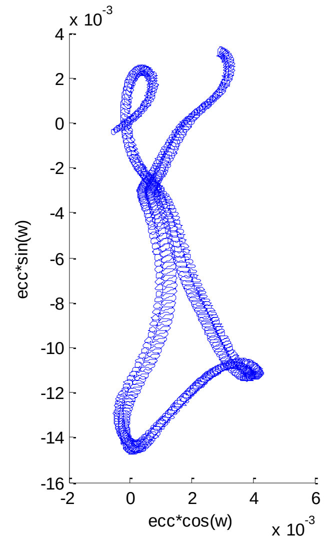


Figure 2-1: Lunar Geoid, LP150Q (meters)

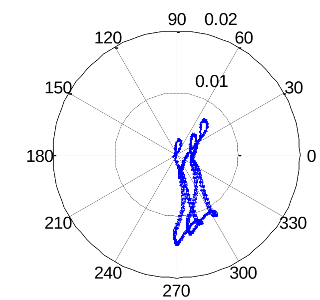
Image from 'Lunar constants and model document'. Jet Propulsion Laboratory, 2005

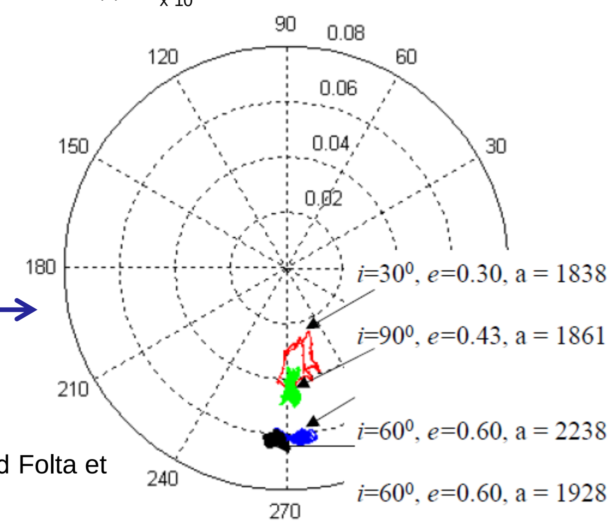
Orbital stability

- 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



200 km initial circular orbit altitude. RAAN = 0 deg. Inclination = 27 deg





Bottom image from ‘Lunar Frozen Orbits’. David Folta et al., 2006

Effects of initial RAAN and inclination

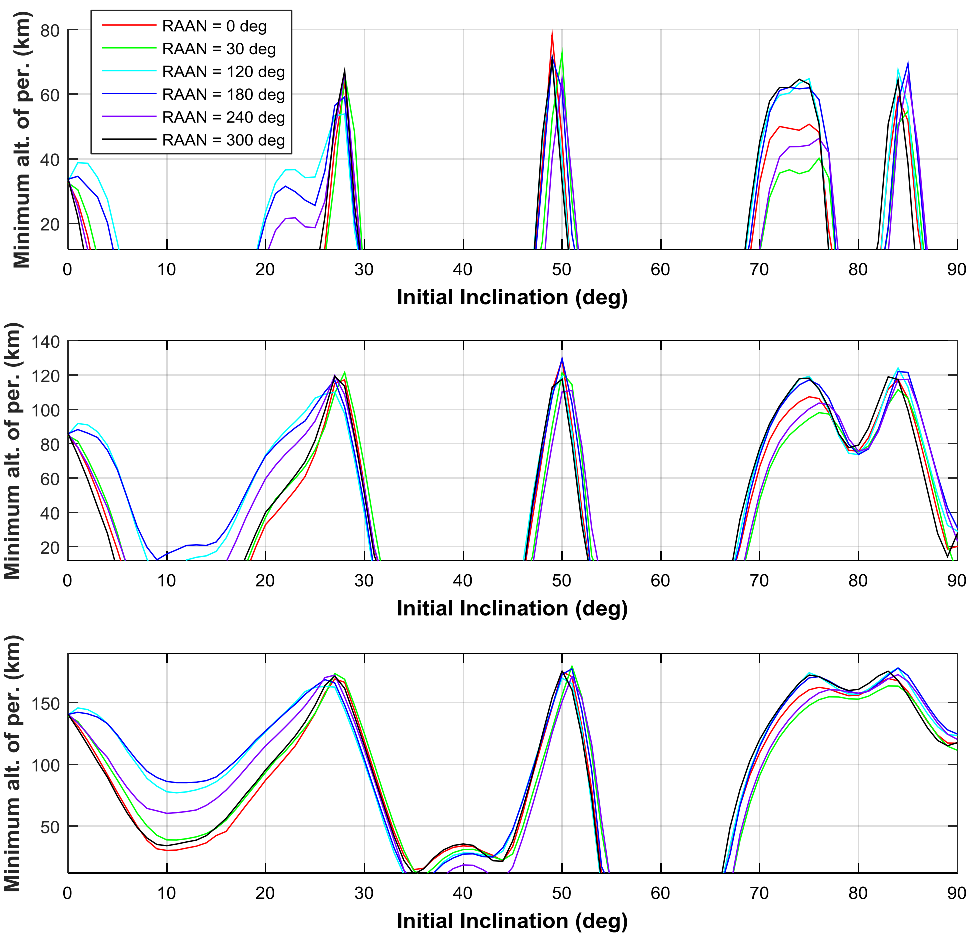
- Simulations carried out for two years with various RAAN/inclination configurations

- 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



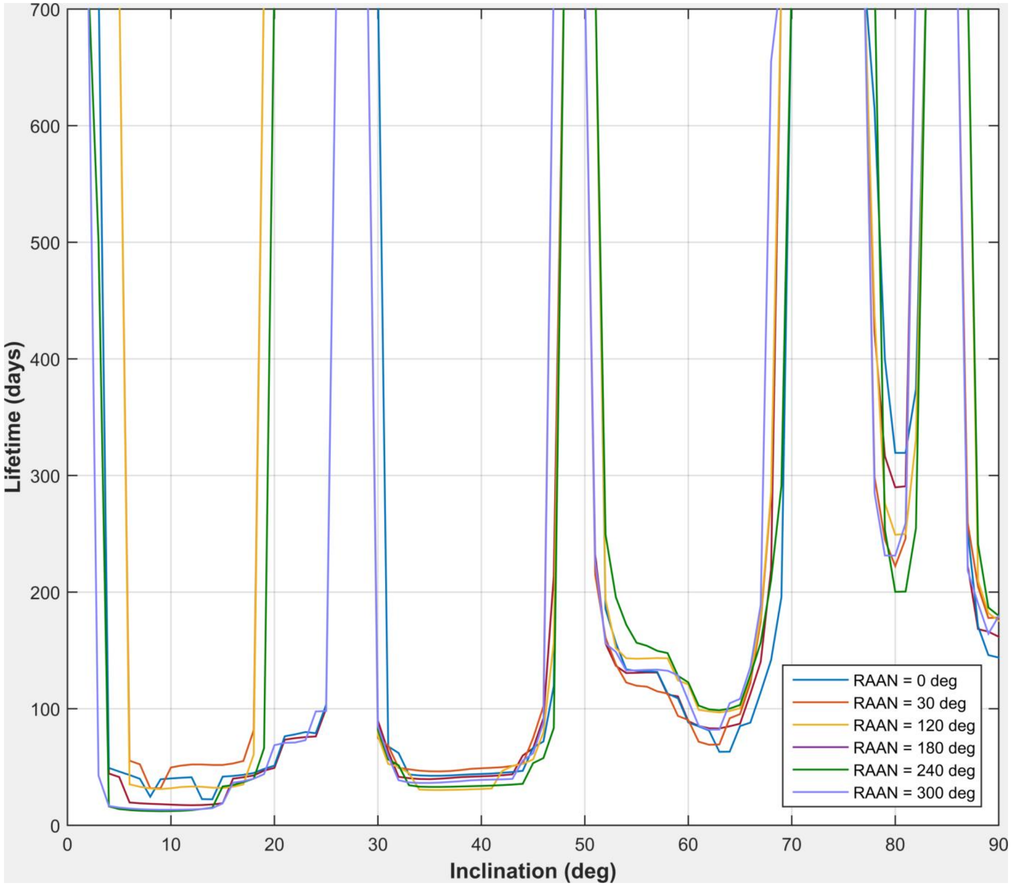
Lifetime

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

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

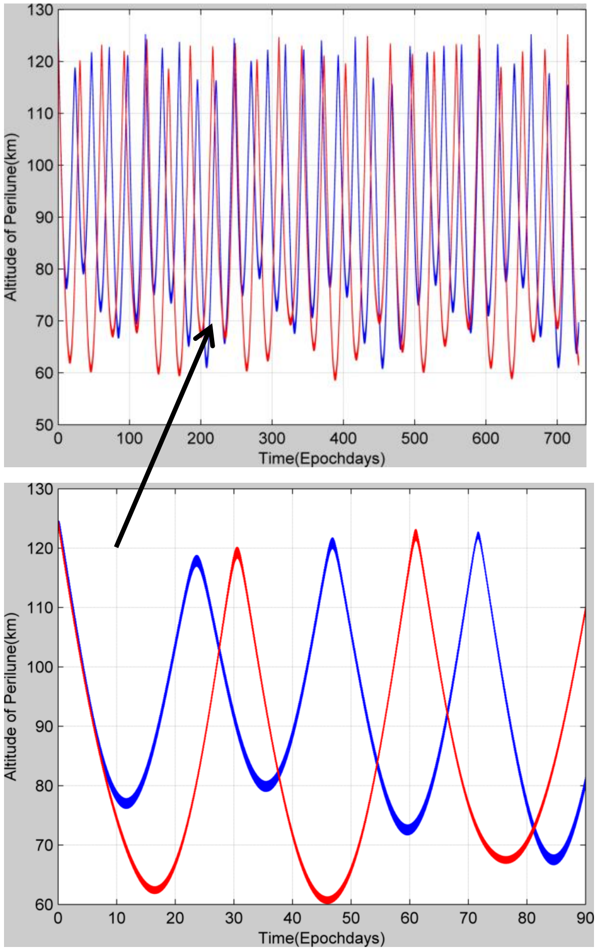
- RAAN still plays an important role, specially at higher inclinations

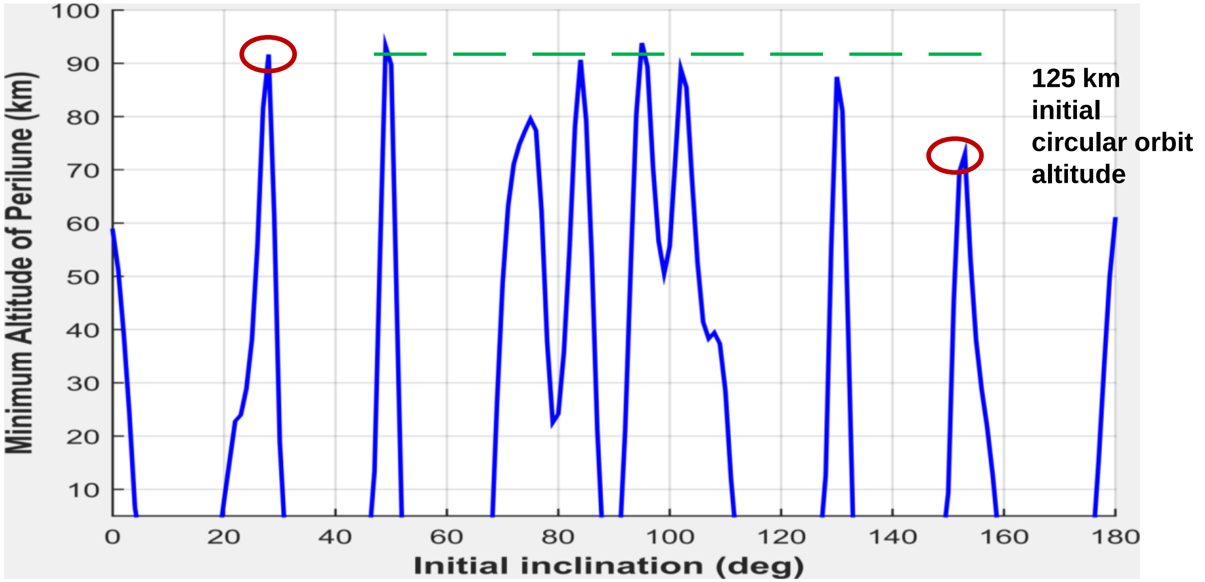
- Some inclinations give very limited lifetime at any possible configuration. Orbital maintenance is mandatory for these cases



Posigrade and retrograde motion

125 km initial circular orbit altitude
Red: 0 degrees of inclination
Blue: 180 degrees of inclination



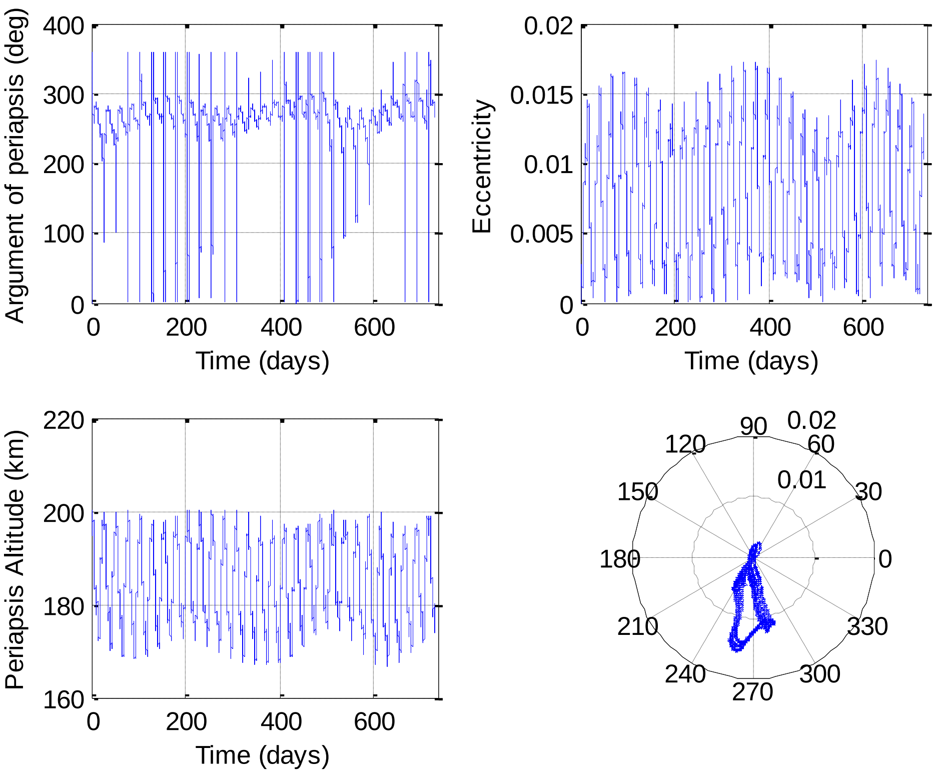


Analysis of minimum altitude of periapsis gives nearly symmetrical results with a slight difference in magnitude

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)

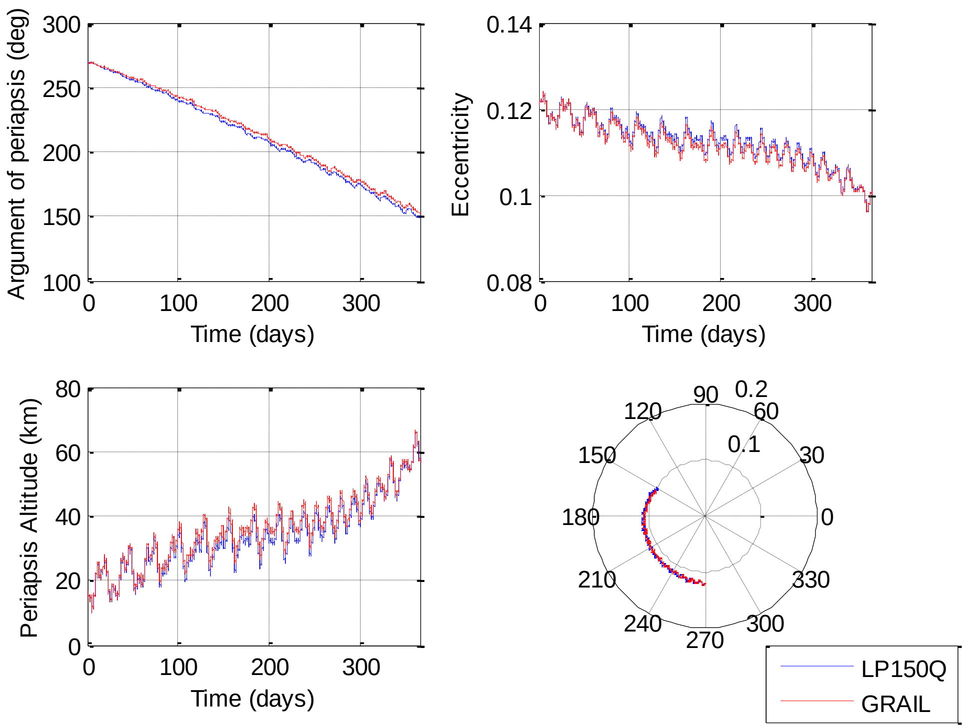


LP150Q/GRAIL gravity models

- 15x500 km elliptical orbit. Ω=270 deg. RAAN = 0 deg. Inc = 90 deg

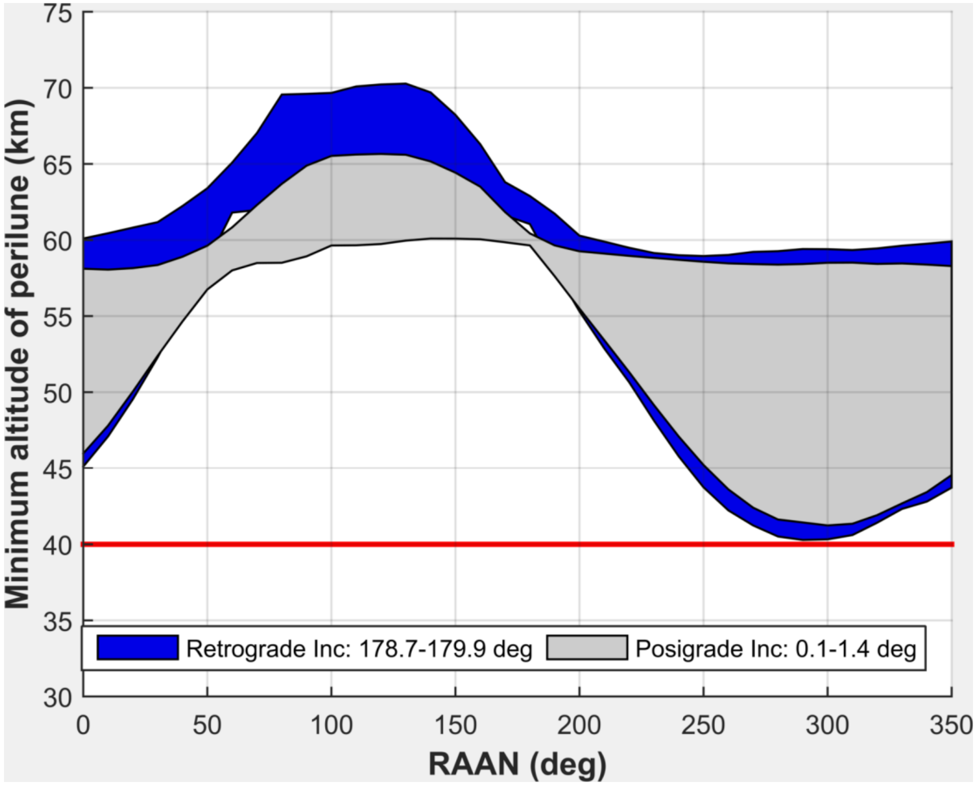
- GRAIL used 200x200 order and degree. LP150Q used 70x70

- 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

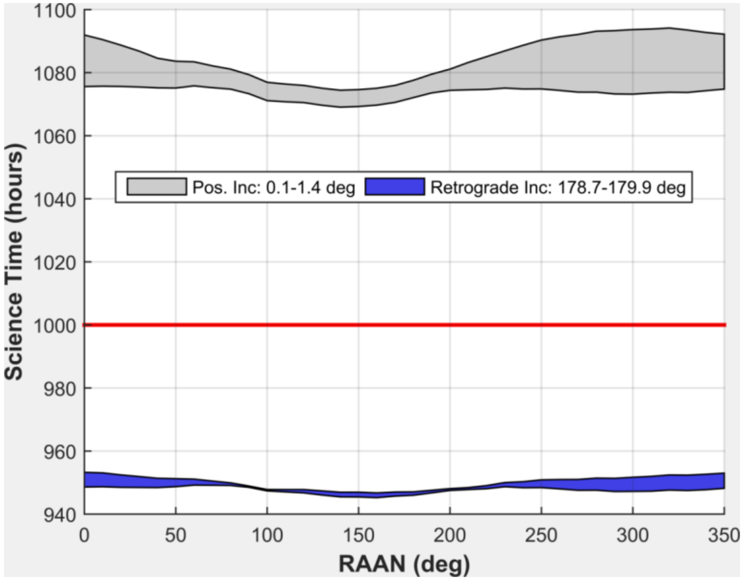


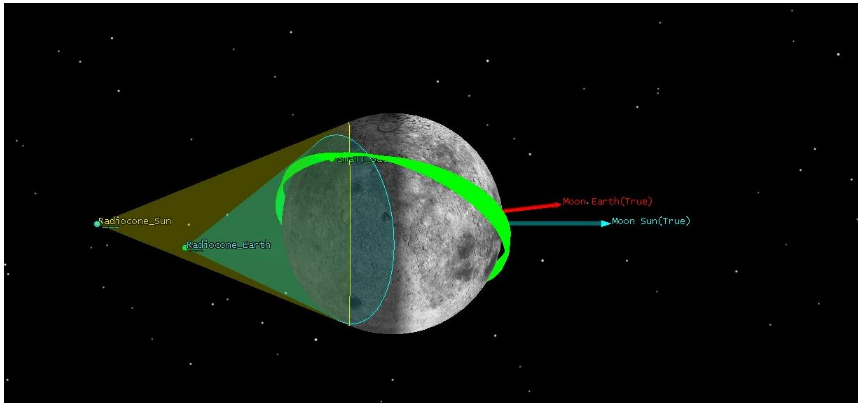
DARE Radio-quiet zone

• 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

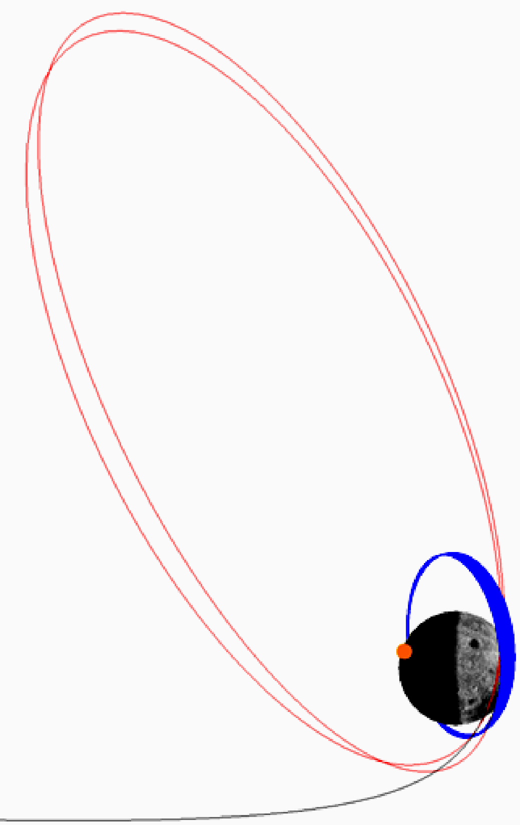
• Even if the retrograde cases were stable like their counterparts, the perturbations were not large enough to make the spacecraft stay within the radio-quiet zone for sufficient time





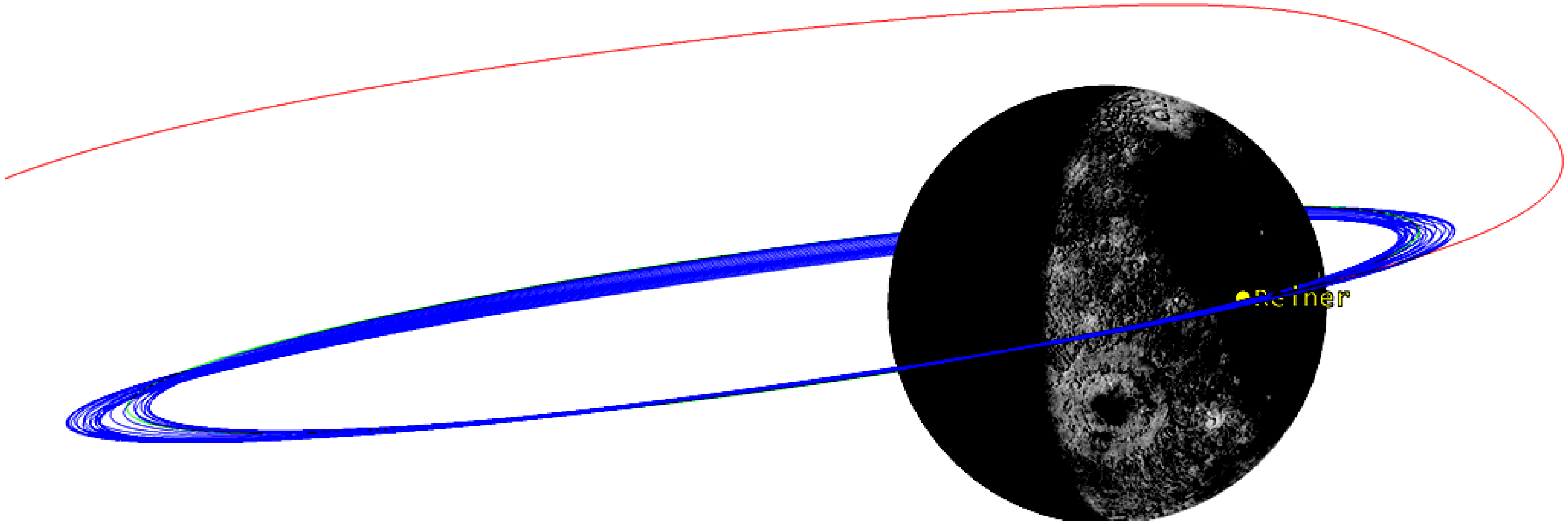
Example:EM-1 deployment and polar frozen orbit

- Trajectory calculated with EM-1 ephemeris
- Flyby to the Moon and capture at close encounter
- Frozen orbit with argument of periapis 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 periapis altitudes ~ 15 km
- ~ 3 m/s maneuvers to maintain periapsis altitude



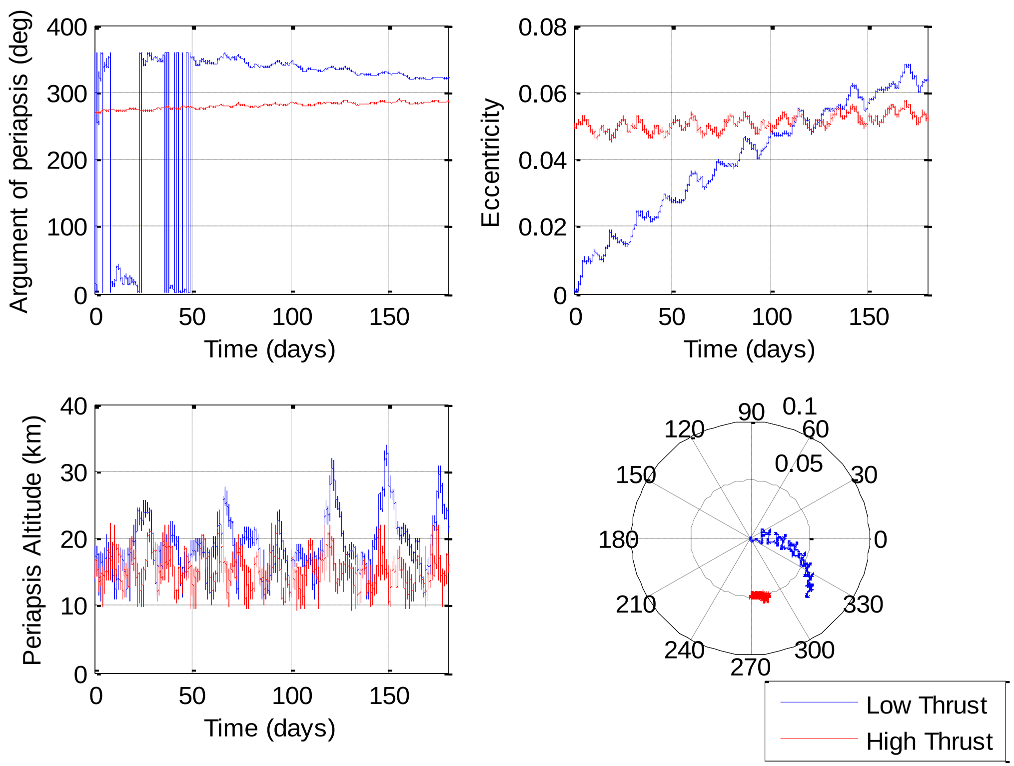
Example: South Pole concept

- 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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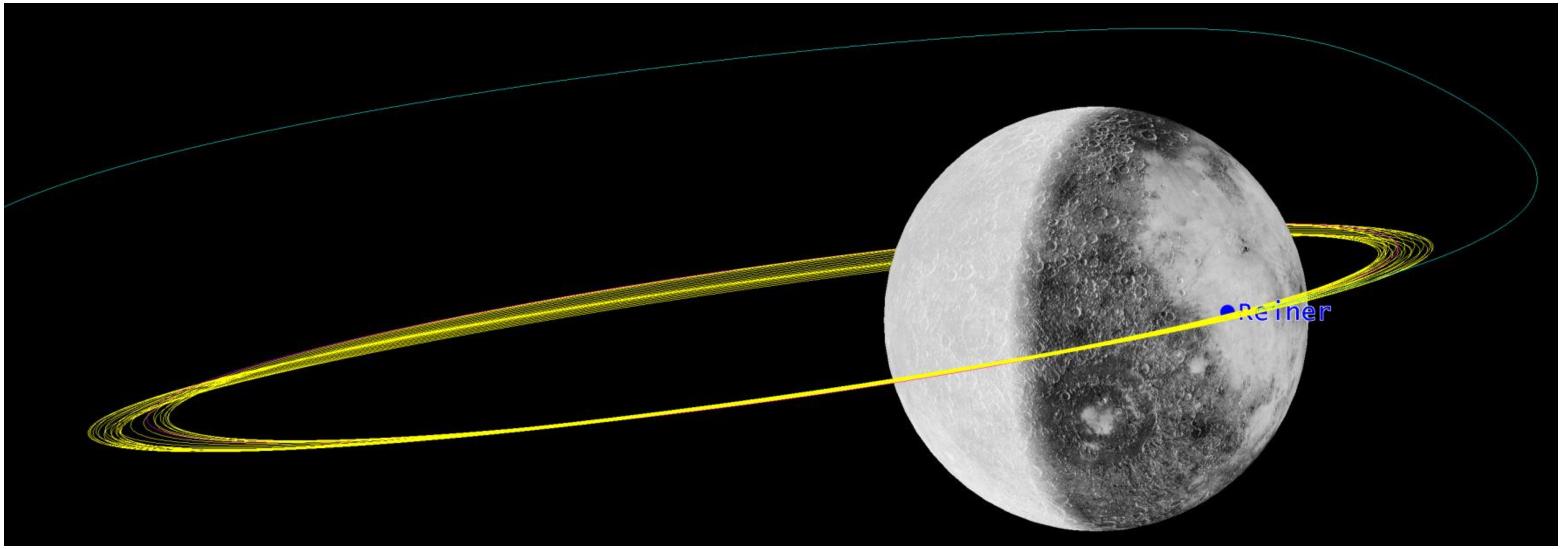

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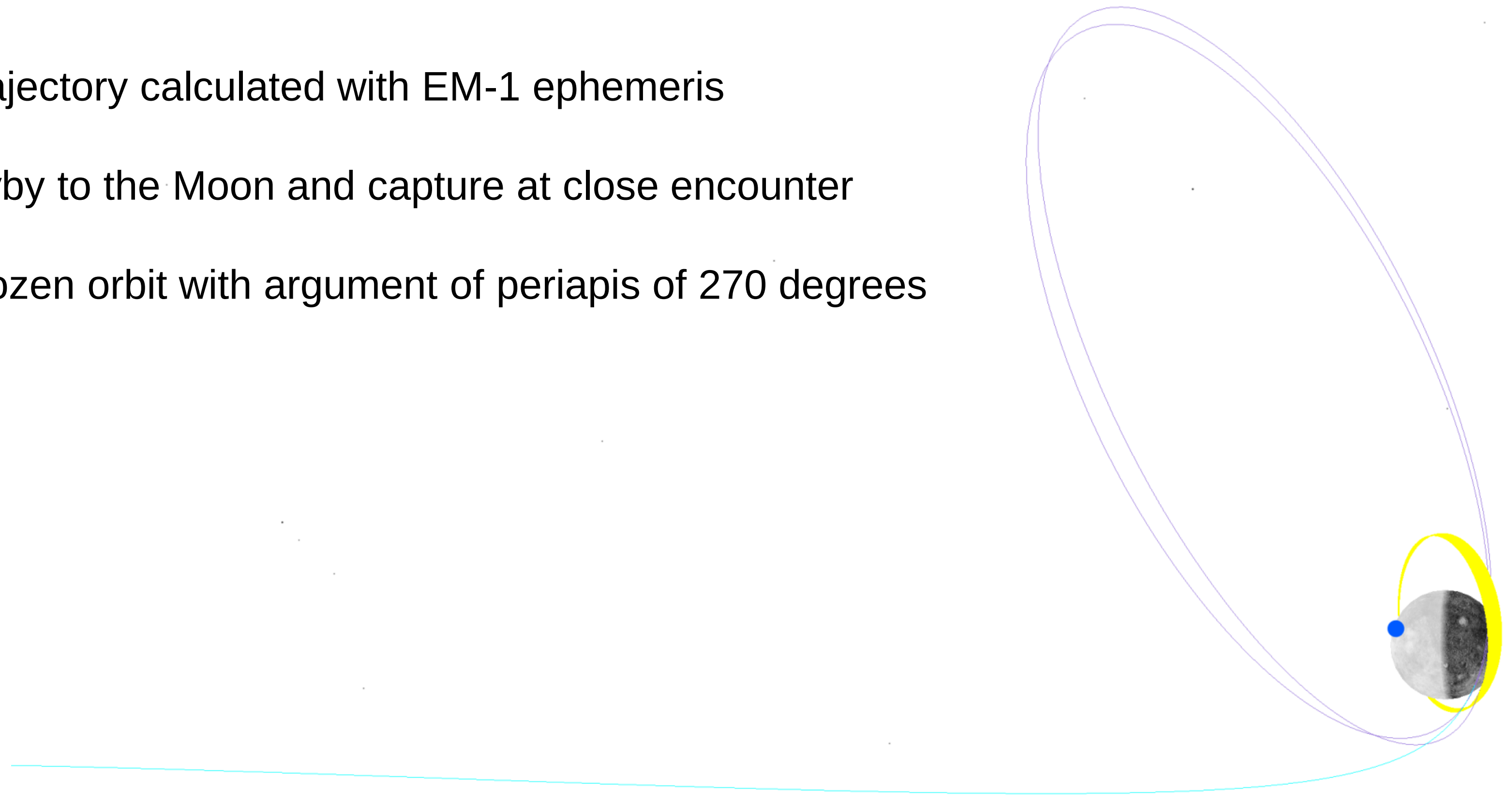

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