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High-altitude near-circular orbits for a lunar orbital station

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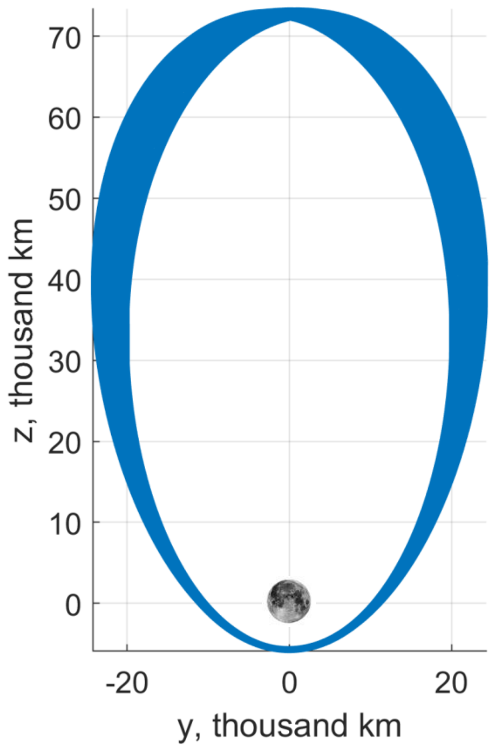
Lunar Orbital Platform-Gateway

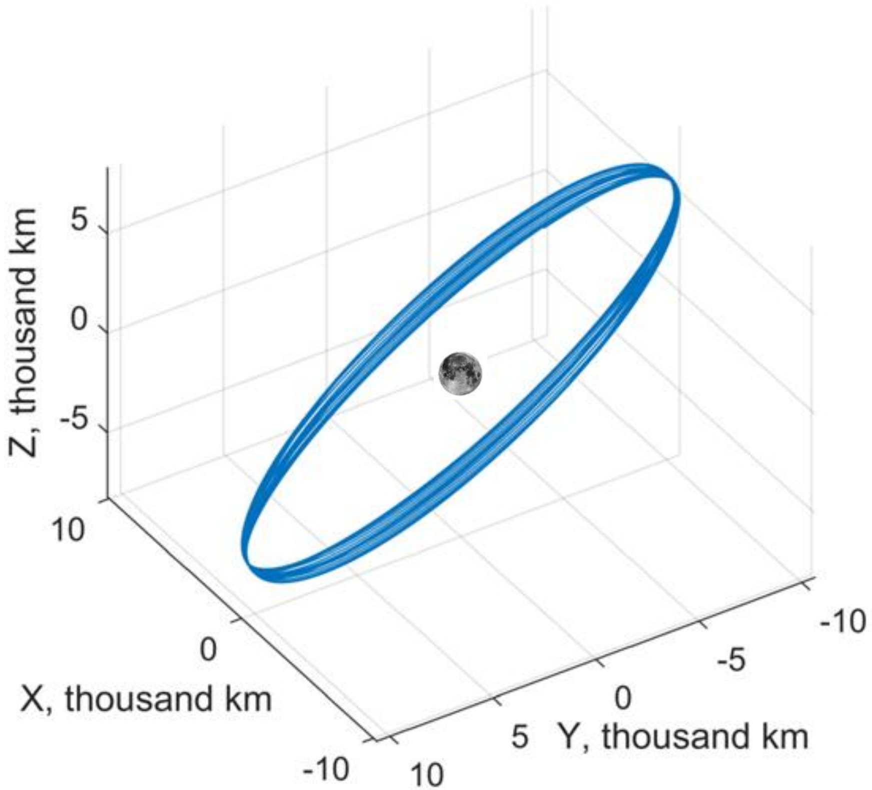
Credit: NASA

- Moon and deep space exploration
- Platform for future crewed and lunar surface expeditions
- Hub for crewed interplanetary missions

High circular orbits for a lunar orbital station



NRHO L2 4:1



High circular, h = 10 thousands km

High circular almost-polar orbits around the Moon (10-15 thousands km above the surface) are considered as an alternative to Near Rectilinear Halo-Orbits (NRHOs)

Problem statement

- We want to <u>analyze</u> the stability, eclipse conditions, and radio visibility of the proposed high circular almost-polar orbits around the Moon and <u>compare</u> them with resonant NRHOs

Reference frames

- International Celestial Reference System (ICRS):
  the current standard inertial celestial reference system

- Selenocentric Celestial Reference System (SCRS):
  Moon-centered inertial system with the axes parallel to the ICRS axes

- Mean-Earth/Mean-Rotation System (MER):
  selenocentric rotating reference frame associated to the mean axis of rotation of the Moon and the average Earth-oriented lunar meridian

High-fidelity model of orbital motion

- JPL's DE430 ephemeris
- Spherical harmonic model GRGM1200A for lunar gravitational field
- Cannonball model for solar radiation pressure

The equations of motion are written in the SCRS in the following form:

$$\ddot{\mathbf{r}} = \mathbf{g}_m - \frac{PA}{m}\frac{\mathbf{r}_s - \mathbf{r}}{|\mathbf{r}_s - \mathbf{r}|} + \frac{\mu_s}{|\mathbf{r}_s - \mathbf{r}|^3}(\mathbf{r}_s - \mathbf{r}) - \frac{\mu_s}{|\mathbf{r}_s|^3}\mathbf{r}_s + \sum_{i=1}^{8}\left(\frac{\mu_i}{|\mathbf{r}_i - \mathbf{r}|^3}(\mathbf{r}_i - \mathbf{r}) - \frac{\mu_i}{|\mathbf{r}_i|^3}\mathbf{r}_i\right),$$

where the indices m, s, and i correspond to the Moon, the Sun, and the i^{th} Solar system's planet, respectively. The gravitational parameters μ_i, i = 1… 8, and μ_s have been taken from the 2018 Astronomical Almanach.

$$P = 4.56 \cdot 10^{-6}\ \mathrm{Pa}$$

$$A/m = 0.006\ \mathrm{m}^2/\mathrm{kg}$$

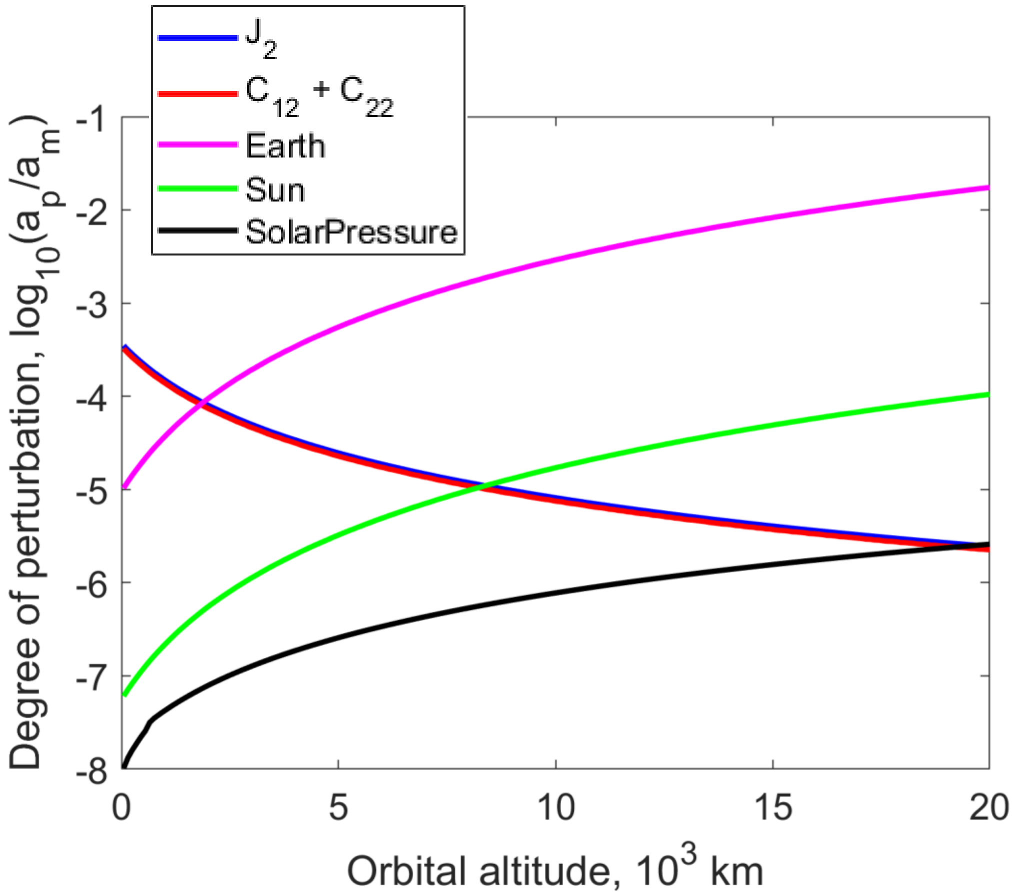
Stability research

- The orbital elements osculate in the high-fidelity model of motion and experience short-period variations depending on the relative level of perturbations

- Stability is defined as a low mean change of the orbital elements in the MER system over a long period of time

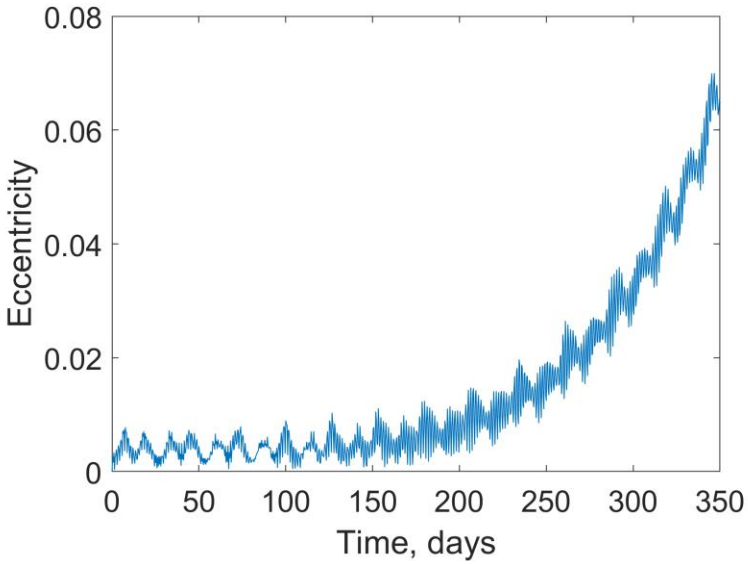
- In order to determine the admissible mean change of the orbital elements over a long period of time, we estimate the values the short-period variations

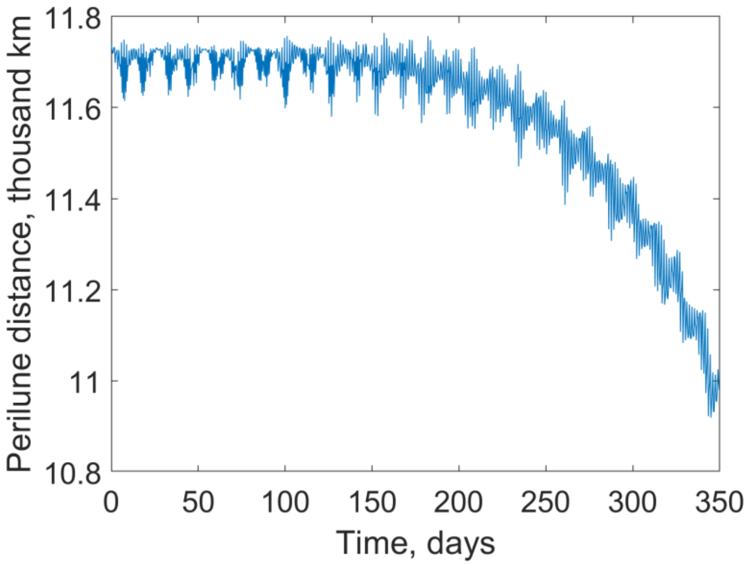
Degree of perturbation at different altitudes

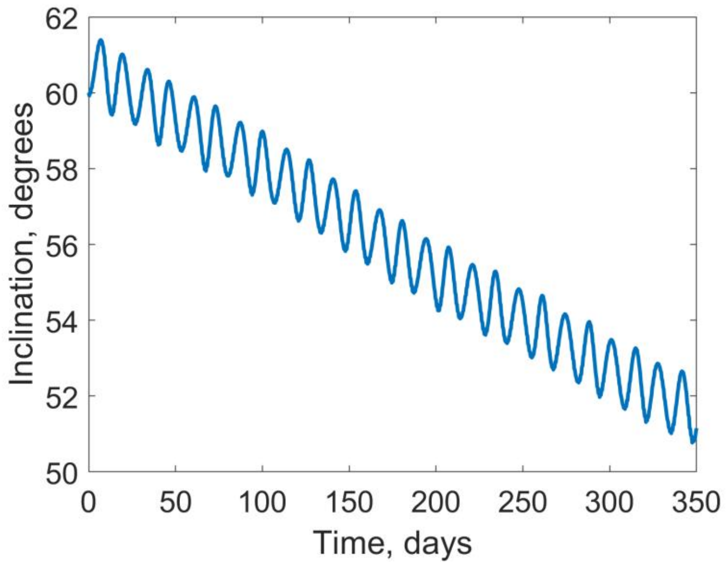


⇨ Short-period variations of inclination and perilune distance are expected to be approximately 1-2° and 2-3%, respectively

The Lidov-Kozai effect







<u>Considered orbits:</u>

inc: 60º:10º:120º

h_p: 10:0.2:15 th. km

Initial Ω: 0º and 90º

Initial date: 01.01.2028

80% of the orbits have the averaged month absolute variation of inc equals to 2º, and relative variation of h_p equals to 3%

Eclipse conditions research

Considered orbits

inc: 60º, 90º, 120º, h_p: 10:1:15 thousands km, initial Ω: 0º and 90º,
initial date: 01.01.2028

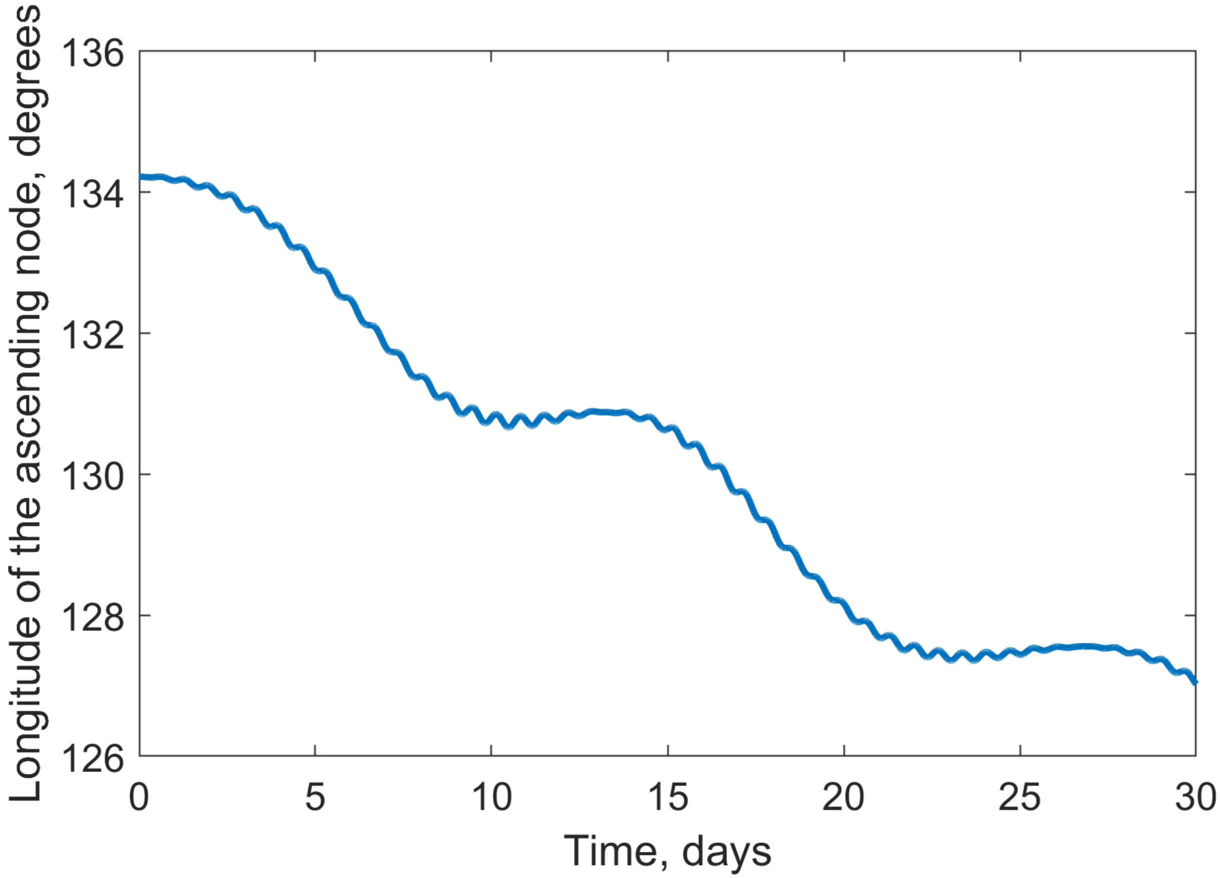
Over the period of 4 months:

- Lunar eclipses last up to 100 minutes
- Earth eclipses last up to 2 hours
- 20% of the orbits cross the Earth's shadows
- Less than 50% of the orbits cross the Moon's shadows
- Lunar eclipses occurred in series.
  A series of the lunar shadows lasts up to 15 days.
- Approximate time between shadow seasons

$$\Delta t \approx \frac{180^\circ}{\omega_E - \dot{\Omega}}$$

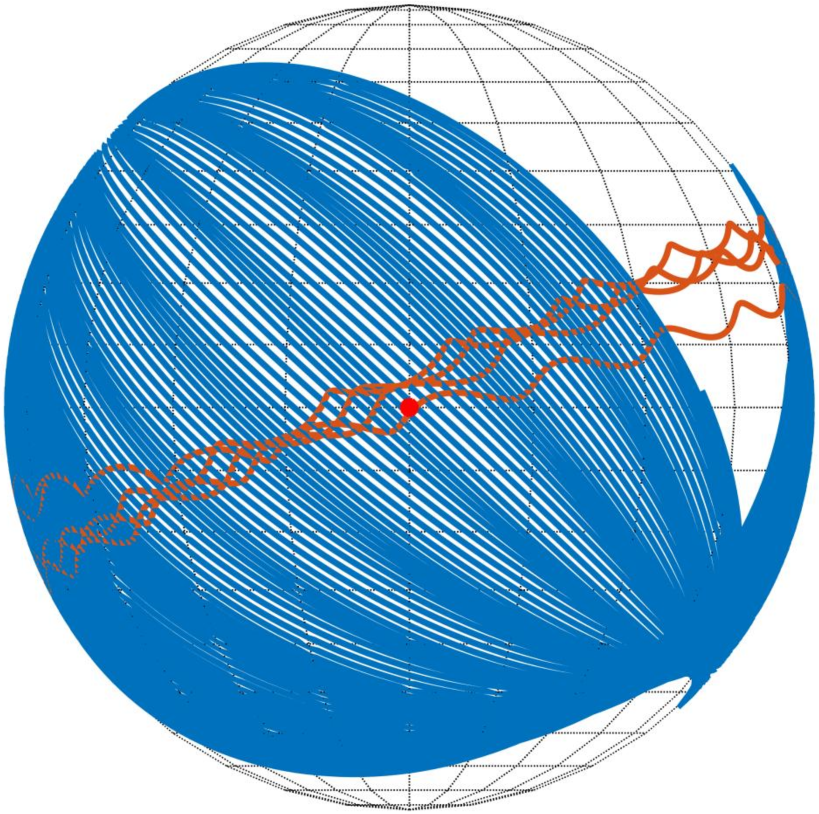
can be determined by the orbital frequency of the Earth and the LAN's rate

Precession of the longitude of the ascending node in the inertial system of reference



For the considered orbits the rate of change of Ω varies from 5° to 10° per month. Thus, for these orbits, Time between series of eclipses by the lunar shadow is about 4-5 month.

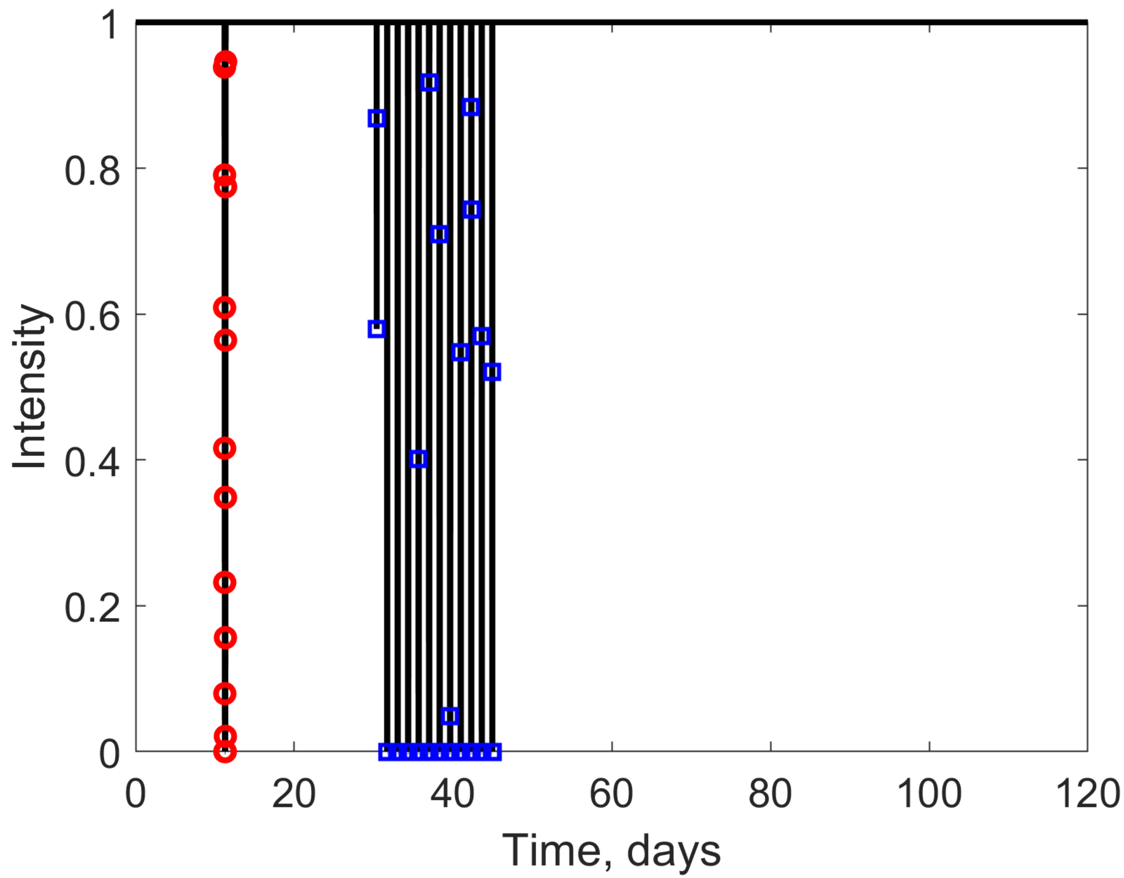
The Moon’s and the Earth’s centers as seen from the spacecraft



Visible movement of the centers of the Moon (blue) and the Earth (brown) in the celestial hemisphere with the center in the Sun (red dot) on the interval of 4 month for the high circular orbit with perilune altitude of 10 thousand km, the inclination of 60° and the initial date of 01.01.2028

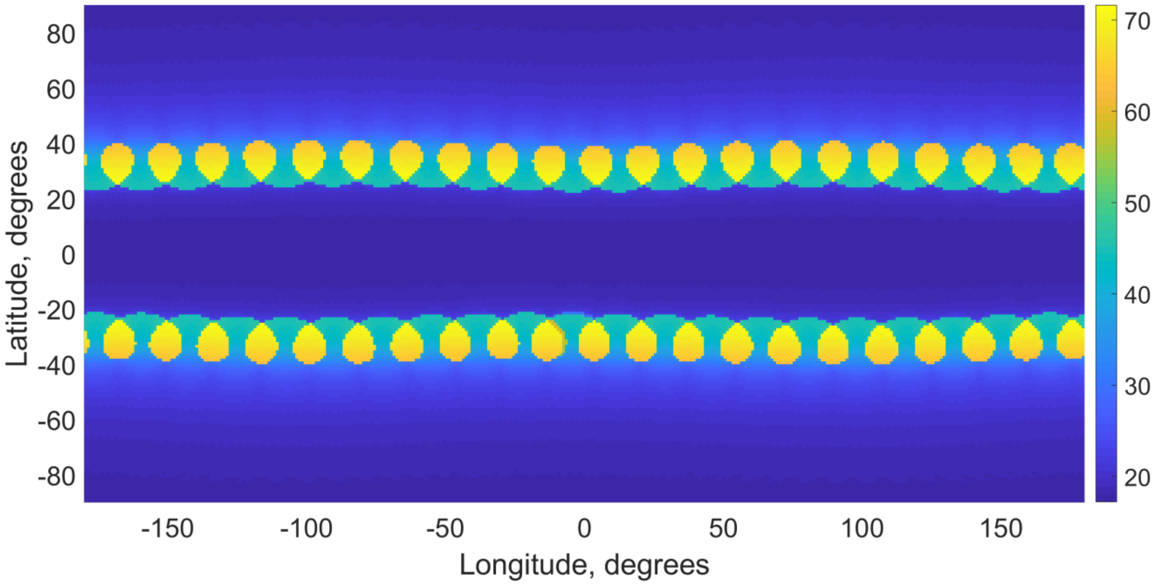
Light intensity over time

Intensity is defined as a fraction of the solar disk which is seen.

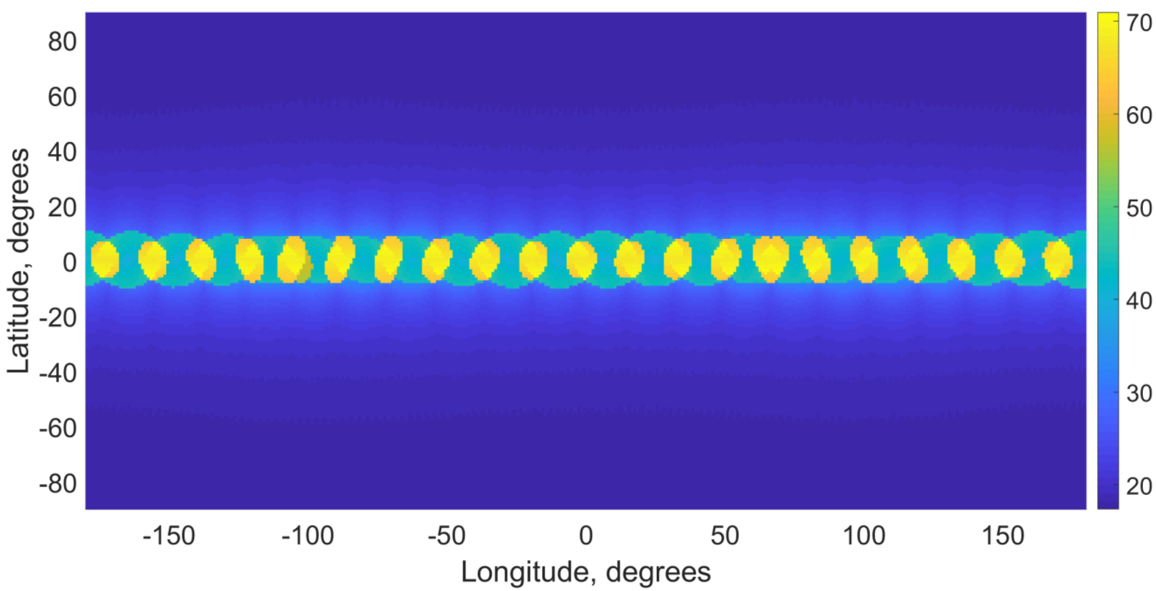


Intensity along the high circular orbit with perilune altitude of 10 thousand km, the inclination of 60º and the initial date of 01.01.2028

Radio visibility of the lunar surface

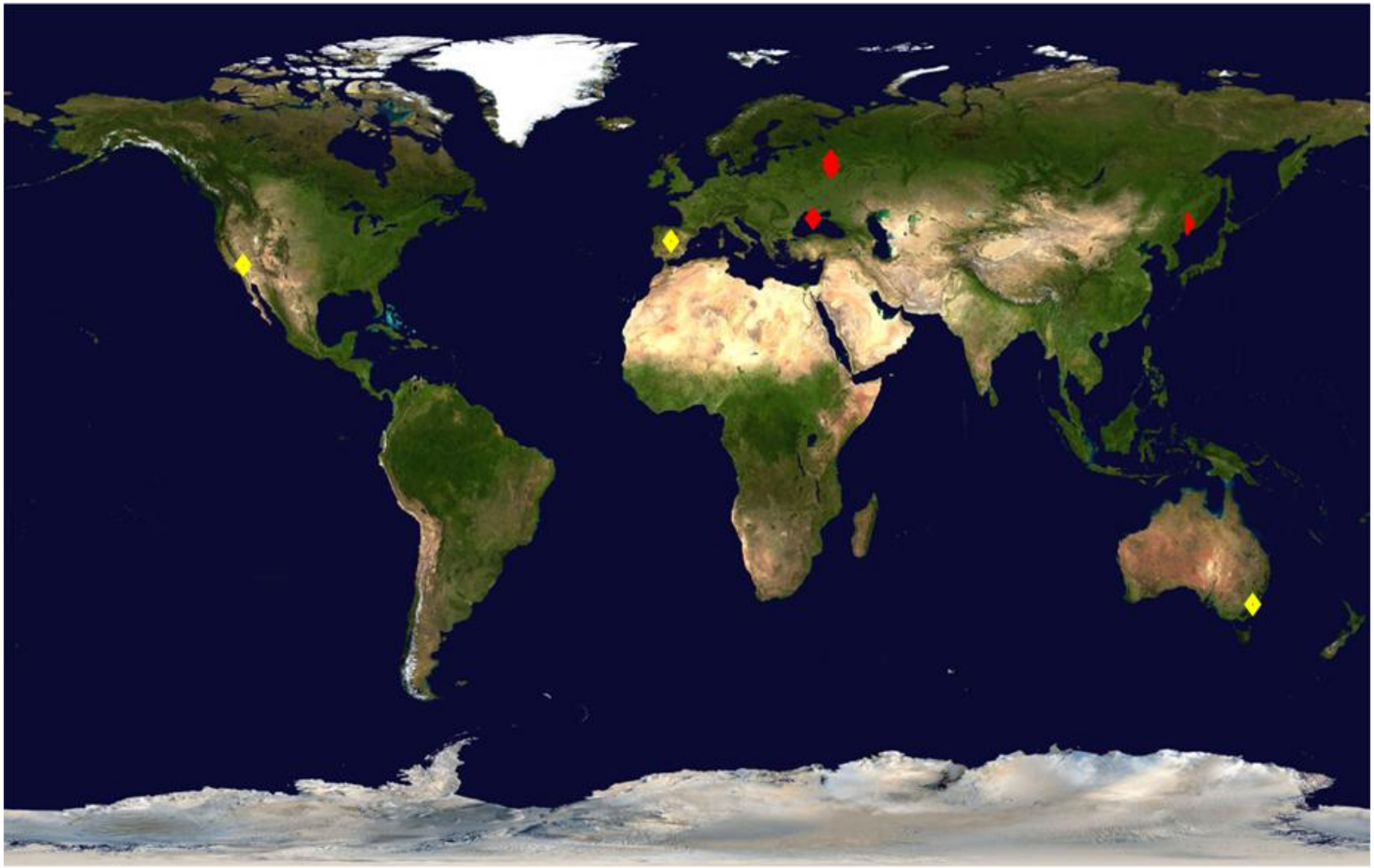


inclination 60º



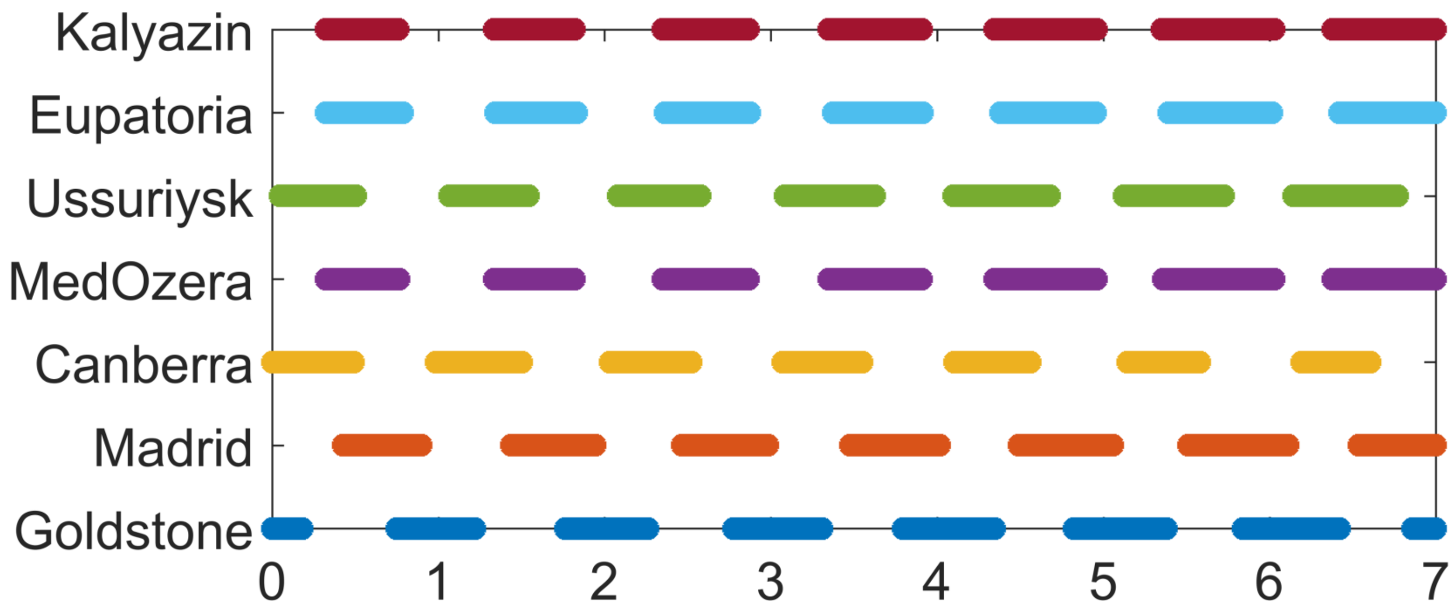
inclination 90º

Selected deep space communication centers



Russian centers for deep space communications (red) and NASA's Deep Space Network (yellow)

Radio visibility from the Earth



Radio visibility periods for the high circular orbit with the perilune altitude of 10 thousand km, the inclination of 60°, and the initial date of 01.01.2028. The figure corresponds to the weekly observations from different centers for deep space communication

Conclusion

- The high circular orbits are stable for several months in the sense that the mean change of the orbital elements is weak (2° for the inclination and 3% for the perilune distance). However, over a long period of time, the evolution of high circular orbits obeys the Lidov-Kozai effect.
- For considered high circular orbits it is possible to avoid the Moon's and Earth's shadows for approximately 4 months. The duration of stay in the shadow may be up to 2 hours and 100 minutes for the Earth and the Moon, respectively. A series of lunar eclipses occurs every 4-5 months.
- All points of the Moon's surface can be observed from the high circular orbits around the Moon due to the Moon rotation.
- The pause in the radio visibility from the Earth may vary from 130 to 160 minutes when passing the far side of the Moon. Continuous radio visibility can be achieved using NASA Deep Space Network.

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Backup

- International Celestial Reference System (ICRS): Its origin is at the barycenter of the Solar System, with axes that are intended to be "fixed" with respect to space. ICRS coordinates are approximately the same as equatorial coordinates (J2000.0 Julian epoch). The axes of the system are fixed in space relative to quasars.
- Equatorial coordinates: a fundamental plane consisting of the projection of Earth's equator onto the celestial sphere (forming the celestial equator), a primary direction towards the vernal equinox, and a right-handed convention.
- Mean-Earth/Mean-Rotation System (MER): selenographic coordinates — latitude and longitude in the coordinate system with the main plane orthogonal to the averaged direction of the lunar axis of rotation, and the zero meridian oriented on average to the center of the Earth.

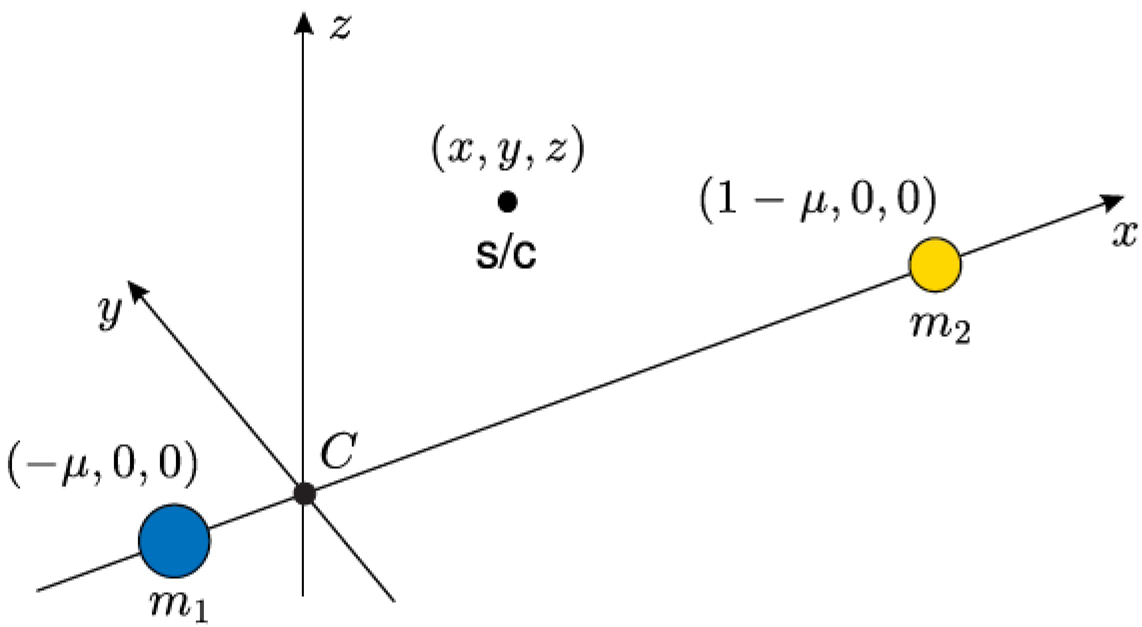

Fig. 2: Rotating frame in the circular restricted three-body problem.