HIGH-ALTITUDE NEAR-CIRCULAR ORBITS FOR A LUNAR ORBITAL STATION

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High-altitude almost polar circular orbits around the Moon (10-15 thousands km above the surface) are currently proposed as a potential location of a prospective lunar orbital station alternative to near-rectilinear halo orbits. The goal is to compare various high-altitude circular obits and the resonant near-rectilinear halo orbits L2 9:2 and L2 4:1. To make a comparison, we investigate stability properties of the proposed orbits, eclipse conditions, and radio visibility of the lunar surface and station radio visibility from the Earth ground stations, including the Deep Space Network and stations located in Russia.

INTRODUCTION

At present, all the world major space agencies (NASA, Roskosmos, JAXA, ESA and others) are developing the project of an habitable lunar orbital station called the Lunar Orbital Platform-Gateway, formerly known as Deep Space Gateway[1][*]. The station is planned to be used as a platform for future crewed lunar surface missions and as a hub for deep-space flights.

Up to now, near rectilinear halo orbits (NRHOs) have been primarily considered as potential locations for a lunar station.[2–8] The main advantages of the NRHOs are the conditions of continuous radio visibility of a station from the Earth, low station-keeping costs, and good conditions for the observation of near-polar regions of the Moon. Moreover, among NRHOs, there are those that do not encounter the shadows of the Moon and the Earth for tens of years.

In the current work, we propose an alternative to NRHOs: high-altitude almost polar circular orbits around the Moon (10-15 thousands km above the surface). The goal is to compare the proposed high-altitude circular orbits and the resonant NRHOs L2 9:2 and L2 4:1. To make a comparison, we investigate stability properties of the proposed orbits, eclipse conditions, and radio visibility of the lunar surface and station radio visibility from the Earth ground stations, including the Deep Space Network and stations located in Russia.

The structure of the paper is as follows. The first section outlines the dynamical model used. The next three sections describe high circular orbits' stability properties, eclipse conditions and radio visibility, correspondingly. All the conclusions made are collected in the corresponding section.

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[*]https://www.nasa.gov/sites/default/files/atoms/files/gateway_domestic_and_international_benefits-memo.pdf

HIGH-FIDELITY MODEL OF ORBITAL MOTION

In order to provide high accuracy of calculations, the high-fidelity ephemeris model is used throughout the orbits analysis. Positions of the Sun and the Solar system's planets, as well as the instantaneous orientation of the lunar principal axes of inertia relative to the International Celestial Reference System (ICRS) coordinate axes, are retrieved from JPL's DE430 ephemeris.[9] For solar radiation pressure, the cannonball model with the area-to-mass ratio $A/m = 0.006$ m^2/kg is used, $P = 4.56 \cdot 10^{-6}$ Pa is adopted as the constant value of solar radiation pressure. The lunar gravitational acceleration $\mathbf{g}_m$ is evaluated based on the spherical harmonic model GRGM1200A truncated to degree and order 8*. The equations of the spacecraft motion are written 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. All the vectors are expressed in the Selenocentric Celestial Reference System (SCRS). It is Moon-centered inertial system with the axis parallel to the ICRS axis. The gravitational parameters $\mu_i, i = 1 \dots 8$ and μ_s have been taken from the 2018 Astronomical Almanach †.

When indicating points on the lunar surface, we use their selenographic latitude and longitude in the so-called Mean-Earth/Mean-Rotation System (MER). The transformation from the Moon's principal axes of inertia to the MER axes is described, for instance, in.[9] The inclination of high circular orbits is also given with respect to the MER equatorial plane.

STABILITY OF HIGH CIRCULAR ORBITS

The prospective lunar station is planned to be used for safe long-term explorations of the Moon and deep space. For these purposes the station's working orbit must be stable in sense of a weak mean change of the orbital elements in MER over a long period of time. The orbits around the Moon are perturbed in high fidelity model of motion, as a consequence the orbital elements are osculating at every instant. Their naturally occurred short-period variations directly depend on the relative level of perturbations. In order to determine the admissible mean change of the orbital elements over a long period of time, we have to estimate what values the short-period variations takes.

We thus examined the contribution of the main sources of perturbations (the lunar principal gravitational field harmonics J_2, C_{21} and C_{22}, the gravitational fields of the Earth and the Sun, solar radiation pressure) in relation to the central lunar gravitational field. To appraise the behaviour of the corresponding perturbing accelerations as a function of the selenocentric distance, we considered the polar circular orbits around the Moon with the altitude from 50 km to 20 thousand km.

Figure 1 shows the degree of disturbances averaged for the period of orbits depending on their orbital altitude. The degree of disturbances is defined as the order of the ratio of the perturbing acceleration magnitude to the magnitude of the central lunar gravitational field acceleration. It is noticeable that, for the altitude more than 3 thousand km, the main disturbing contribution is made by the gravitational field of the Earth. Furthermore the level of perturbing acceleration, relative to the central lunar gravitational field acceleration, is approximately 10^{-1} for the high circular orbits. It means that the short-period variations of inclination and perilune distance is expected to

*`https://pgda.gsfc.nasa.gov/products/50`
†`http://asa.usno.navy.mil/`

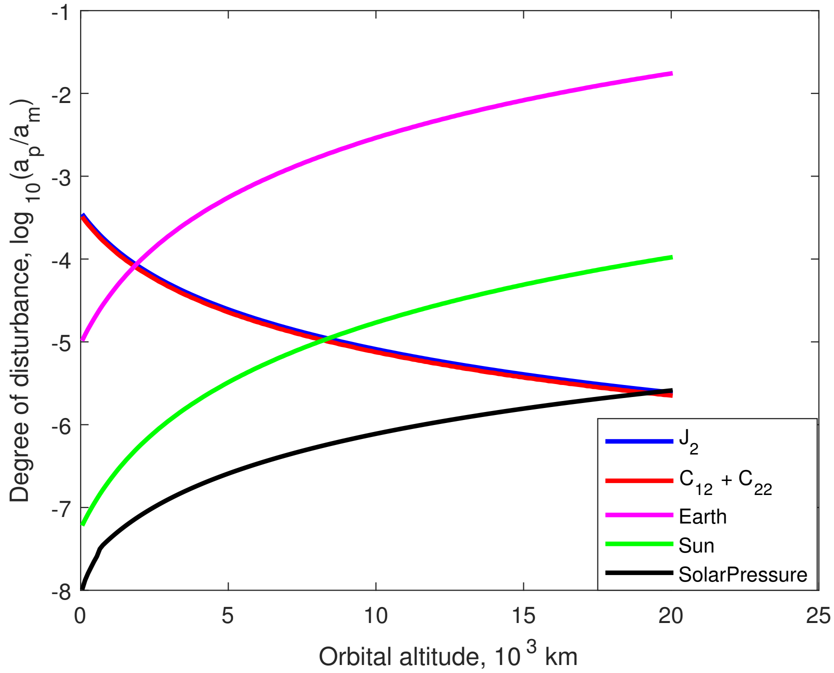

Figure 1. **The order of the ratio of the perturbing acceleration magnitude a_p to the magnitude of the central lunar gravitational field acceleration a_m. Disturbances correspond to the lunar principal gravitational field harmonics J_2 (blue) and C_{12} with C_{22} (red), the Sun's (green) and the Earth's (rose) gravitational fields and solar radiation pressure (black).**

be approximately 1-2 degrees and 2-3%, correspondingly. Thus we could not require more tight restrictions on the mean change of the orbital elements while studying the stability of high circular orbits. The orbits that satisfy the given constraints will be considered stable.

We have studied the stability properties of the set of circular orbits with the altitude varied from 10 to 15 thousand km in increments of 200 km, with the inclination varied from 60 to 120 degrees in increments of 10 degrees and with the initial longitude of ascending node in MER system equal to 0 or 90 degrees ($26 \cdot 7 \cdot 2 = 364$ orbits). The starting date is 01.01.2028.

It is worth emphasizing that the evolution of orbits obeys the Lidov-Kozai effect.[10,11] According to this effect the eccentricity of inclined circular orbits increases while the inclination and perilune distance decrease over the time because of perturbations from the Earth (see Figures 2 – 4). Consequently, a station-keeping is required for the long existence of the station in the high circular orbits. Additionally, the analytical theory of double-averaged restricted three body problem (R3BP)[12] provides the initial orbital parameters that may reduce the Lidov-Kozai effect. This theory can be applied to the orbits of such altitudes, but should be investigated further. The issue of station-keeping and reducing the Lidov-Kozai effect is not considered in the current work.

Due to the Lidov-Kozai effect, the considered high circular orbits strongly evolve over a long period of time as over a year. However, most of them are stable for several month according to our criteria. We have examined the average monthly change of the orbital elements. The result is that 80% of the considered orbits is characterized by the average for the month absolute variation of the inclination and relative variation of the perilune distance of 2 degree and 3%, respectively.

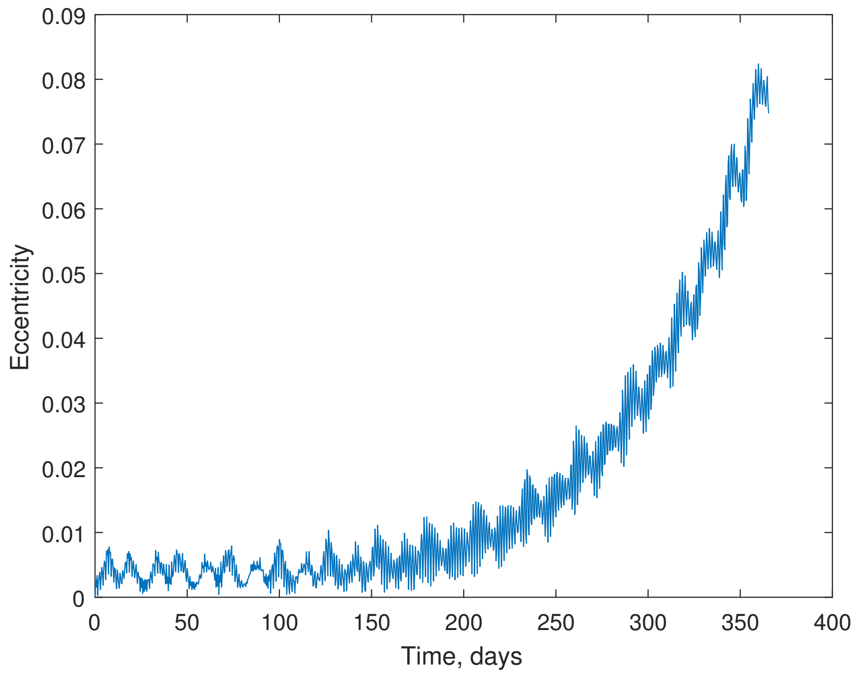

Figure 2. **High circular orbit's characteristic behaviour of the eccentricity depending on time.**

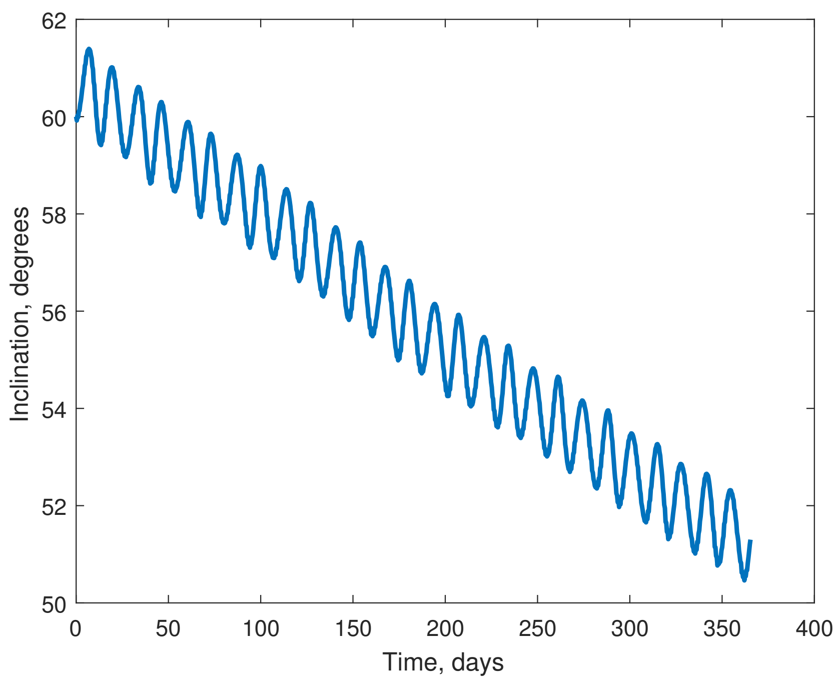

Figure 3. **High circular orbit's characteristic behaviour of the inclination depending on time.**

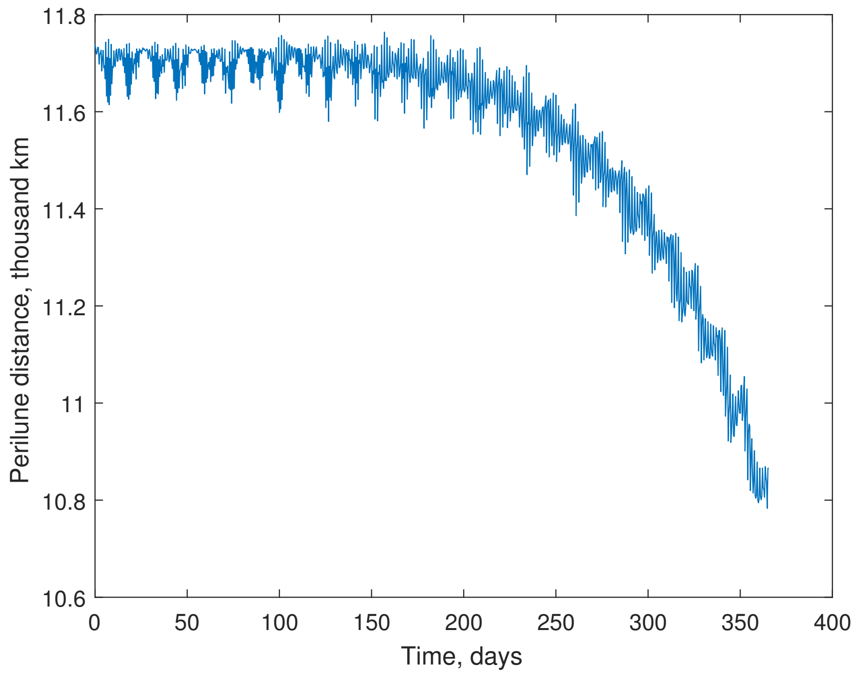

Figure 4. **High circular orbit's characteristic behaviour of the perilune distance depending on time.**

ECLIPSE CONDITIONS

A spacecraft in high circular orbits around the Moon can be subject to eclipses by the shadows of both the Earth and the Moon. The prospective lunar station is planned to be habitable. Because of this, it is important to understand the eclipse conditions in the high circular orbits for two reasons: power generation and the thermal environment.

We have examined the frequency, duration, and depth of eclipses over the period of 4 months for the set of stable orbits with the altitude varied from 10 to 15 thousand km in increment of 1000 km, with the inclination of 60, 90 and 120 degrees and with the initial longitude of the ascending node in MER equal to 0 and 90 degrees ($6 \cdot 3 \cdot 2 = 36$ orbits). Their orbital period varies from 1.33 to 2.27 days. The passings through the Earth's shadow were extremely rare and lasted up to 2 hours. Most of the considered orbits (84%) did not fall into the shadow of the Earth over such a period of time. The eclipses by the lunar shadow occurred for more than half of the considered orbits. In addition to it, stay in the lunar shadow was not a one-time, it was a series of eclipses lasting up to 100 minutes. The total time of periodical falls into the shadow and leaving it was up to 15 days.

In general, the time between the occurrences of a series of eclipses by the lunar shadow in the high circular orbits may be estimated by the formula

$$\Delta t \approx \frac{180^\circ}{(\omega_E - \dot{\Omega})} \tag{1}$$

where ω_E is the angular orbital speed of the Earth and $\dot{\Omega}$ is the time derivative of the longitude of ascending node in SCRS. The longitude of ascending node in SCRS for the high circular orbits around the Moon decreases depending on time, i.e. $\dot{\Omega} < 0$ (see Figures 5 and 6). Thus, according to Equation 1, the eclipses will occur less frequently in the orbits with the smaller absolute value of $\dot{\Omega}$. If the longitude of ascending node does not change depending on time, than Δt possess a value of the half of a year. For the considered orbits $\dot{\Omega}$ varies from 5 to 10 degrees per month. Thus, for these orbits, Δt is about 4-5 month, that corresponds to our calculations.

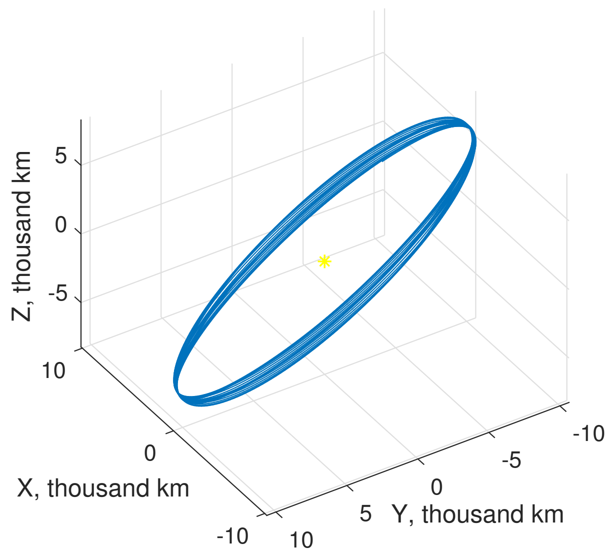

Figure 5. High circular orbit around the Moon (yellow dot) with the perilune altitude of 10 thousand km and the inclination of 60 degrees in SCRS on the monthly period of time.

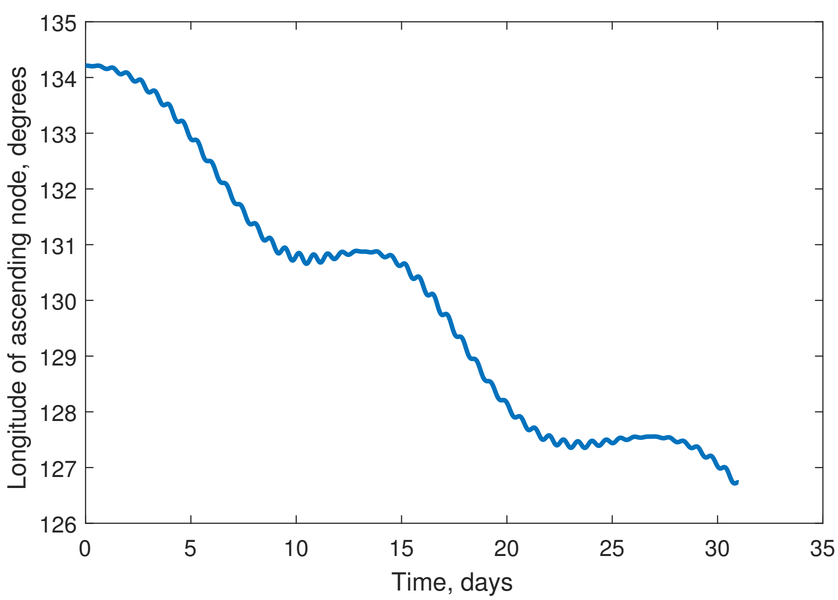

Figure 6. Evolution of the longitude of ascending node depending on time in SCRS for the high circular orbit with the perilune altitude of 10 thousand km and the inclination of 60 degrees.

Figure 7 shows the example of visible movement of the centers of the Moon (blue) and the Earth

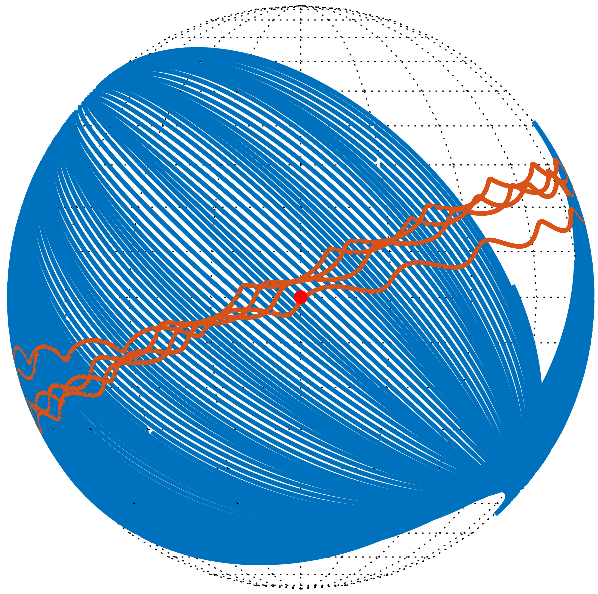

Figure 7. **Visible movement of the centers of the Moon (blue) and the Earth (brown) in the celestial hemisphere with the center in the Sun (red dot) on the interval of 4 month for the high circular orbit with perilune altitude of 10 thousand km, the inclination of 60 degrees and the initial date of 01.01.2028.**

(brown) in the celestial hemisphere with the center in the Sun (red dot) on the interval of 4 month. The figure corresponds to the high circular orbit with the perilune altitude of 10 thousand km, the inclination of 60 degrees and the initial date of 01.01.2028. One cell on the sphere has an angular size of 10 degrees. At the same time, the apparent angular dimensions of the Sun, Moon and Earth are 0.3, 8.5 and 1 degree, respectively. The motion of the center of the Moon occurs from right to left, and the movement of the center of the Earth occurs from left to right. At same stage the blue or red lines will cross the red dot and the station will fall into the shadow (see Figure 8). Figure 8 shows a fraction of the solar disk seen when moving along the same orbit. Blue and red labels correspond to the Moon and Earth eclipses, respectively. The labels was set aside in 10-minute increments when the spacecraft was moving in the Moon's or Earth's shadow. For the considered orbit the duration of stay in the Earth's and lunar shadows was 2 hours and up to 80 minutes, correspondingly.

It is also worth noting that for higher orbits the duration of stay in the Moon shadow increases and the eclipse frequency decreases. This is due to the fact that the speed in the high orbits is less, therefore the station stays in the shadow longer. And the periods of high orbits is greater, so the repeatability of crossing the shadow is less often (it happens after about once per period). Thus it is preferable to choose lower orbits for location of the lunar station.

In reference to NRHOs, for the resonant orbit L2 4:1 it is possible to choose the initial date so that the station will not cross the Earth's and the Moon's shadows at all.[7] This is the advantage of this halo orbit. As mentioned above, for high circular orbits around the Moon, the shadow areas can

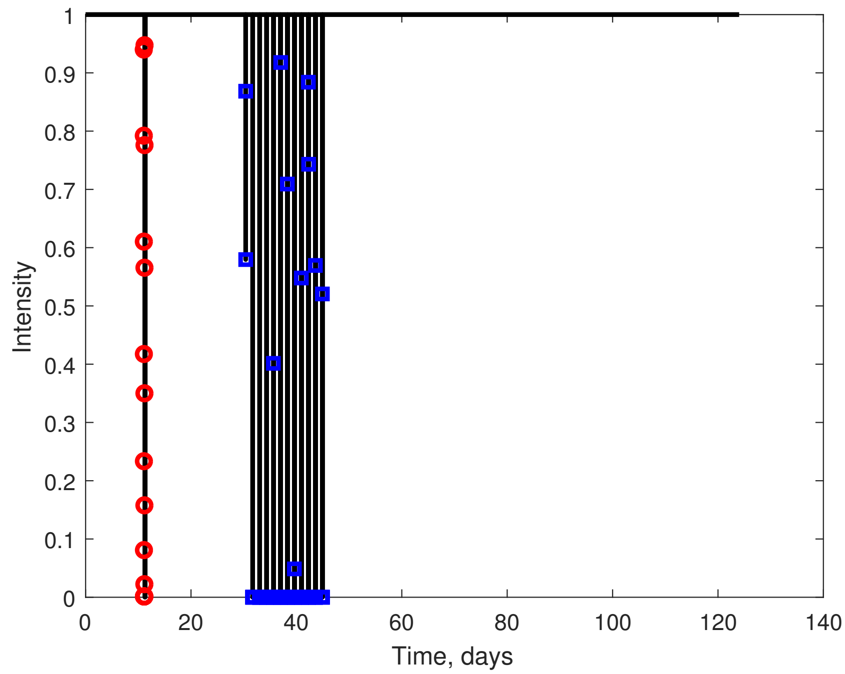

Figure 8. A fraction of the solar disk seen when moving along the high circular orbit with perilune altitude of 10 thousand km, the inclination of 60 degrees and the initial date of 01.01.2028.

be avoided for 4-5 months, but then the series of lunar shadows begins.

RADIO VISIBILITY

Due to the Moon's rotation, all points of the lunar surface can be observed from the high circular orbits around the Moon. However, each point will not be observed continuously, but only when the sub-satellite route passes next to it. Thus, the information about how long we can not observe each point is of great interest. Figures 9 and 10 show the projection of the lunar surface. For each point, the color indicates the maximum time in hours between the periods of the point's observability during the total time of 1 month. The figures correspond to the orbit with inclination of 60 and 90 degrees, correspondingly. It can be seen that the polar regions are well observable and the least often observed points are the points with the latitude equal to the difference between 90 degrees and the inclination of the working orbit. The visibility of each point of lunar surface is the advantage of the high circular orbits around the Moon over NRHOs. NRHOs have almost fixed sub-satellite trajectories. Consequently, visibility conditions of lunar regions in halo-orbits are stationary and same points of lunar surface are poorly observable.

As for the station's radio visibility from the Earth, it may be provided from at least one of the centers of deep space communication at almost any time (see Tables 1 and 2). The situations of close Sun-Moon conjunctions are the exception. More than that, the station in high circular orbits will not be visible while passing the far side of the Moon. For the orbits with the altitude from 10 thousand km to 15 thousand km the pause in the radio visibility may vary from 130 to 160 minutes. It is disadvantage of high circular orbits in contrast to NRHOs. This situations may be avoided in halo-orbits since they are almost fixed in a rotating coordinate system.

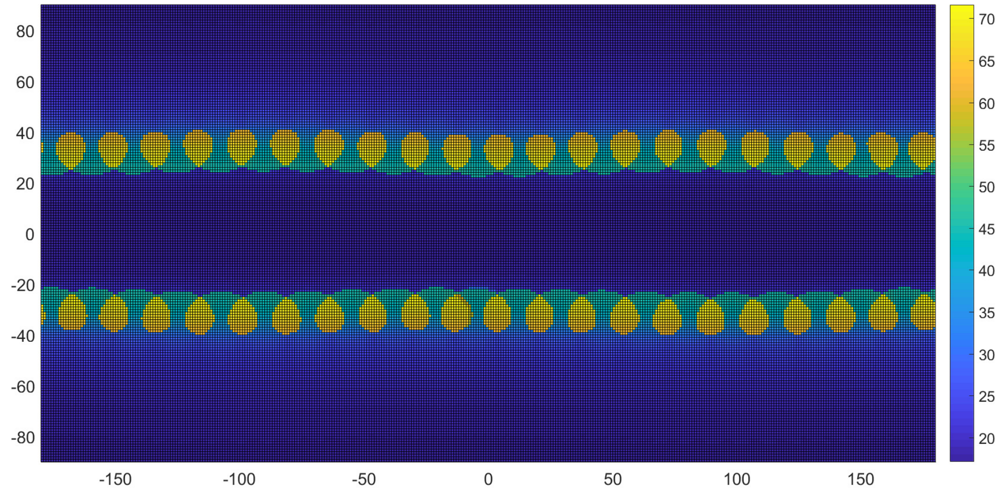

Figure 9. **Projection of the lunar surface. For each point, the color indicates the maximum time in hours between the periods of the point's observability during the total time of 1 month. The figure corresponds to the high circular orbit with perilune altitude of 10 thousand km, the inclination of 60 degrees and the initial date of 01.01.2028.**

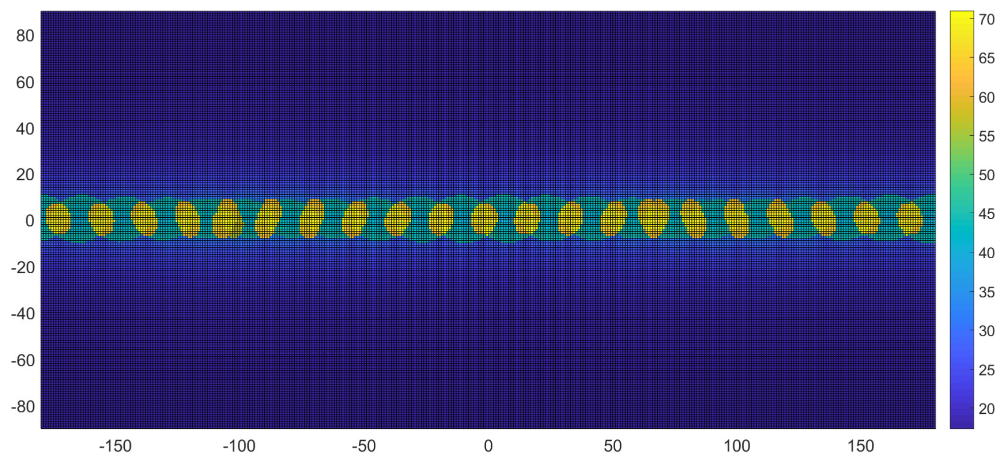

Figure 10. **Projection of the lunar surface. For each point, the color indicates the maximum time in hours between the periods of the point's observability during the total time of 1 month. The figure corresponds to the high circular polar orbit with perilune altitude of 10 thousand km and the initial date of 01.01.2028.**

It is worth mentioning, that the longest continuous visibility of the high circular orbits from the Earth can not be provided only by using the Russian centers of deep space communication. That is due to the absence of the Russian national centers for remote space communications in the western hemisphere (see Table 1 and Figure 11). The connection to the NASA Deep Space Network (DSN) systems for remote space communications will significantly improve the situation (see Table 2). Three 70-meter DSN antennas are located near the Fort Irvine National Military Center (California,

Table 1. Russian centers for deep space communications.

Observation point	Code name	Latitude	Longitude
Center for remote space communications ”Medvegii Ozera”	MedOzera	$55°52'5''$ N	$37°57'6''$ E
East Center for Remote Space Communications	Ussuryisk	$44°0'58''$ N	$131°45'27''$ E
Center for remote space communications ”Eupatoria”	Eupatoria	$45°13'14''$ N	$33°9'56''$ E
Kalyazin Radio Astronomy Observatory	Kalyazin	$57°13'23''$ N	$37°54'1''$ E

Table 2. NASA Deep Space Network.

Observation point	Code name	Latitude	Longitude
Goldstone Deep Space Communication Complex	Goldstone	$35°25'33''$ N	$116°53'22''$ W
Canberra Deep Space Communication Complex	Canberra	$35°24'9''$ S	$148°58'53''$ E
Madrid Deep Space Communication Complex	Madrid	$40°25'53''$ N	$4°14'53''$ W

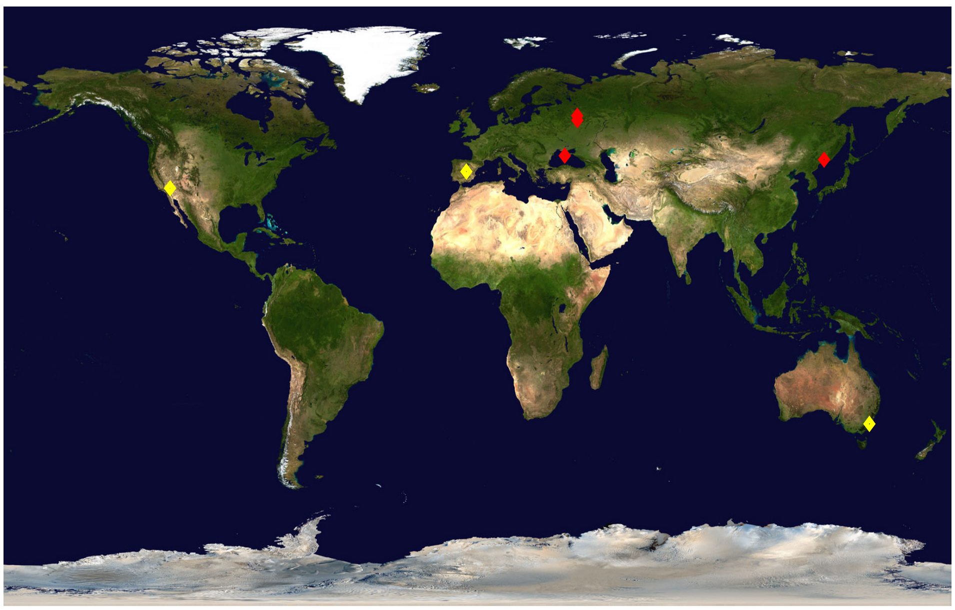

Figure 11. Map of Russian centers for deep space communications (red) and NASA Deep Space Network (yellow).

USA), on the edge of the Tidbinbilla Nature Reserve (Australian Capital Territory, Australia) and in the city of Robledo de Chavela (Madrid province, Spain). Figure 12 shows the radio visibility periods in the high circular orbit with the perilune altitude of 10 thousand km, the inclination of 60 degrees and the initial date of 01.01.2028. The figure corresponds to the weekly observation from the different centers for remote space communication including Russian deep space communications centers and NASA DSN.

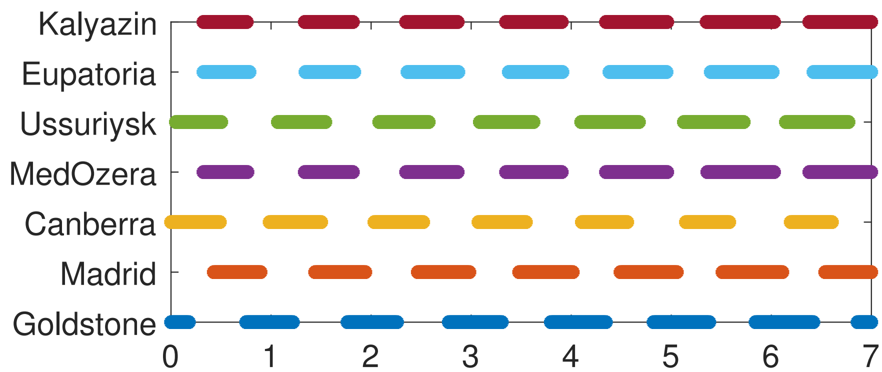

Figure 12. Radio visibility periods of the high circular orbit with the perilune altitude of 10 thousand km, the inclination of 60 degrees and the initial date of 01.01.2028. The figure corresponds to the weekly observations from different centers for deep space communication.

CONCLUSION

The high circular orbits are stable for several months in the sense that the mean change of the orbital elements is week (2 degrees 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. Thus, the eccentricity of inclined circular orbits increases while the inclination and perilune distance decrease. Consequently, a station-keeping is required for the long existence of the station in the high circular orbits. Additionally, the analytical selection of initial orbital parameters, in accordance with double-averaged R3BP, can be applied to reduce the Lidov-Kozai effect.

For considered high circular orbits it is possible to avoid Moon's and Earth's shadow areas 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. Besides, a series of lunar eclipses occurs every 4-5 months. The period of avoidance of the lunar shadow is possible to be increased up to a half a year. This can be achieved by the station-keeping that keeps constantly the longitude of the ascending node of the orbit in SCRS. An inescapable entering in the Earth's and lunar shadows is the disadvantage of high circular orbits comparing to NRHOs. For the halo-orbit L2 4:1 it is possible to choose the initial date so that the orbit will not cross the Earth's and Moon's shadows at all.

As it was mentioned above, all points of the Moon's surface can be observed from the high circular orbits around the Moon due to the Moon' rotation. This is the advantage of the high circular orbits over NRHOs that have fixed sub-satellite trajectories. The polar regions of the Moon are well observable from the high circular orbits and the least often observed points are the points with the latitude equal to the difference between 90 degrees and the inclination of the working orbit.

As for the radio visibility of high circular orbits from the Earth, the situation is similar to that for

NRHOs, except the cases when the station is not visible due to the passing beside the far side of the Moon. In these cases, the pause in the radio visibility may vary from 130 to 160 minutes for the orbits with the altitude from 10 thousand km to 15 thousand km. As well as in the case of NRHO, the longest continuous visibility of the high circular orbits from the Earth can not be provided only by using the Russian centers of deep space communication. That is due to the absence of the Russian national centers for deep space communications in the western hemisphere. However, the connection to the NASA Deep Space Network (DSN) systems for deep space communications can provide almost continuous observability from the Earth.

ACKNOWLEDGMENT

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