Analysis of Orbital Movement Lunar Orbital Station

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Abstract. Represents the new project “Deep Space Gateway (DSG)” - an orbital station in the vicinity of the Moon [1]. The DSG can be used as a staging post for exploration missions to the lunar surface and eventually to other deep space destinations including Mars. It is also a platform in a location where the human and technological challenges of long duration human missions in deep space can be investigated and addressed [2]. A DSG may be placed farther from the Moon in halo orbit relative to its position on the line of the Moon-Earth, known as the L₂ Lagrange point. One of the modern orbits of interest as a destination for a spacecraft in cis-lunar space is the Near Rectilinear Halo Orbits (NRHO) [4]. This work is devoted to the study of issues related to the orbital movement DSG, to understand which orbit will be optimal.

1. Introduction
The International Space Station (ISS) was a valuable asset for testing the necessary research and technology for more remote flight scenarios. However, the ISS requires constant replenishment and maintenance and is designed to work exclusively in low Earth orbit (LEO) conditions. Consequently, for the next stage of a manned space flight, intelligence capabilities in addition to the capabilities of the ISS are needed.

Since the return of the Apollo 17 spacecraft to Earth in December 1972, not a single person has gone beyond the limits of low Earth orbit. As a springboard for such research, the focus is currently on developing the ability to support the crew in orbit around the Moon [3].

ESA is seeking information from the European research community to inform about the development of the Deep Space Gateway — the spacecraft in the vicinity of the Moon, which will host crewed missions and operate without crew in between. The Deep Space Gateway is planned to be built and operated during the 2020’s as humanities next step beyond Low Earth Orbit and out into the Solar System. Deep Space Gateway is created as a strategic platform, from which human exploration of the Solar System can set forth. Its location in the lunar vicinity, and outside the deep gravitational borehole of the Earth, allows it to be used as an intermediate post for exploratory expeditions to the lunar surface and, ultimately, to other distant space directions, including Mars. It is also a platform where human and technological problems of long-term human missions in deep space can be explored and solved.

The platform is being prepared in the framework of international cooperation under the leadership of partner agencies of the international space station: ESA, NASA, JAXA and CSA [1, 7].

The DSG gets its name because its position is beyond the deepest part of the Earth’s gravity. This means that you need less energy to start a mission from there. This makes it an excellent starting point for sending human expeditions to the lunar surface and more distant places such as Mars, i.e. for training for the future flight to Mars. It can also act as a receiving facility for the initial examination (quarantine for the purposes of planetary defence) of samples returned from Mars or other planets.
2. Orbital motion Deep Space Gateway

Deep Space Gateway will be placed in special points in space. For example, where the gravitational pull between the Earth and the Moon is balanced. In some cases, the DSG may be placed farther from the Moon in halo orbit relative to its position on the line of the Moon-Earth, known as the $L_2$ Lagrange point. The balance of gravitational forces here allows to "park" the spacecraft to make observations.

Table 1. Orbit Types considered for Deep Space Gateway.

| Orbit Type                  |
|-----------------------------|
| Near Rectilinear Halo Orbits, NRHO |
| Distant Retrograde Orbit, DRO |
| $L_2$ Halo                  |
| Low lunar Orbit, LLO        |

![Orbit Types considered for Deep Space Gateway.](image)

Figure 1. Orbit Types considered for Deep Space Gateway.

One of the modern orbits of interest as a destination for a spacecraft in habitat in the cis-lunar space, is the Rectilinear Halo Orbits (NRHO). A subset of the halo orbit family, NRHO, is attractive as intermediate orbits for several reasons, including advantageous movements from the Earth and to destinations beyond the Earth’s proximity, communication lines, the possibility of limiting eclipse time and favorable access to the lunar surface [4].

This type of trajectory was first identified in a simplified representation of gravitational effects in the Earth-Moon system, that is, in the Circular Restricted Three Body Problem (CR3BP). The study of the motion of the apparatus around the $L_2$ point will be carried out in the barycenter system of the Earth, Moon bodies.

2.1. Circular Restricted Three Body Problem (CR3BP)

In the model of CR3BP, NRHO are characterized by favorable stability properties, which imply the ability to support NRHO-like movement for a long time, while consuming few fuel resources.

The dynamic model in CR3BP serves as a reasonable approximation to dynamic models with higher fidelity in the Earth-Moon system, including those that may also include solar gravity. As part of this application, the CR3BP considers the motion of a massless spacecraft under the gravitational influence of the Earth and the Moon. It is assumed that these two primary bodies, modeled as point masses, move in circular orbits around their common barycenter. The motion of the spacecraft is then described relative to the coordinate system $\hat{x} - \hat{y} - \hat{z}$, which rotates with the movement of the Earth and the Moon, as shown in Fig. 1[5]. In this frame, the spacecraft is located in dimensionless coordinates ($x$, $y$, $z$). By convention, the values in CR3BP are dimensionless, so the distance between the Earth and the Moon, as well as the mean motion of the primaries, are both equal to a constant.
value of unity. In addition, the masses of the Earth and the Moon are dimensionless and equal to 1 - \( \mu \) and \( \mu \), respectively, where the parameter \( \mu \) is equal to the ratio of the mass of the Moon to the total mass of the system. In a rotating frame of reference, the scalar equations of motion for a spacecraft are written as:

\[
\begin{align*}
\ddot{x} - 2\dot{y} &= \frac{\partial U}{\partial x}, \\
\ddot{y} + 2\dot{x} &= \frac{\partial U}{\partial y}, \\
\ddot{z} &= \frac{\partial U}{\partial z}.
\end{align*}
\]

(1)

\[
\text{где } U = \frac{1}{2}(x^2 + y^2) + \frac{1-\mu}{d} + \frac{\mu}{r}, \\
\text{где } d = \sqrt{(x + \mu)^2 + y^2 + z^2}, \\
\text{где } r = \sqrt{(x - 1 + \mu)^2 + y^2 + z^2}.
\]

\[\text{Figure 2. Geometry in CR3BP for the Earth-Moon system}\]

2.2. Some NRHO Qualities and Rating Resources Available in Deep Space Gateway

The creation of a viable intermediate orbit in the cis-lunar space is a key step in the human journey beyond the limits of a low Earth orbit. Both in terms of access from the Earth, access to other destinations, and influencing the design of a spacecraft is all important. Although more work will be done to better understand the properties of cis-lunar orbits, the near rectilinear orbit (NRHO) seems to be the most favorable orbit to fulfil many competing, constraints and requirements[1].

Some relevant properties of NRHO in table 2

| Orbit                     | Property                          | Value                          |
|---------------------------|-----------------------------------|--------------------------------|
| Near Rectilinear Halo Orbits, NRHO | Period                           | 6-8 days                       |
|                           | Orbit around                      | Moon                           |
|                           | Distance to the surface of Moon   | Approx. From 2000 to 75 000 km |
|                           | Inclination                       | Approx. 90 °                   |
|                           | Visibility from Earth             | Constant                       |
| Earth-Moon L₂ halo orbit  | Period                           | 8-14 days                      |
|                           | Orbit around                      | Libration point L₂ Earth-Moon  |
|                           | Distance to Moon                  | 60000 km                       |
|                           | Visibility from Earth             | Constant                       |
3. Near Rectilinear Halo Orbits

This type of trajectory was first identified in a simplified representation of gravitational effects in the Earth-Moon system, that is, in the Circular Restricted Three Body Problem (CR3BP) problem. The study of the motion of the apparatus around the L₂ point will be carried out in the Earth-Moon barycenter system.

The NRHO, in the vicinity of the Moon, potential long-term orbits for a ship with a crew in the wing zone are determined [4].

\[4\]

3.1. Orbit characteristics

NRHOs have such advantages as relatively inexpensive transfer options from Earth, possible transfer options to the lunar surface and other orbits in cis-lunar space and beyond, and advantageous eclipse properties. Including part of the large L₂ halo-orbit family depicted in Figure 3, the NRHO subset may be roughly limited to specific locations reflecting changes in linear stability across the L₂ halo family. [4].

A family of related periodic orbits bifurcates, in fact, from the L₂ near rectilinear halo orbits; members of this family appear in Figure 3(a, b). In appearance, members of this family are a “butterfly” in shape; in particular, this family of orbits fords from a specific NRHO, which has a period of approximately 6 days. The butterfly's orbit family has characteristics similar to those NRHO, offering similar advantages for designing a trajectory in this neighborhood. The orbital movement of the butterfly resembles the shape of the figure eight, but these orbits wrap around the near and far sides of the Moon, as can be seen in Figure 3(c). Figure 3(c). The family of orbits of southern butterflies when viewed in configuration space [5].

4. Orbital analysis

The near-rectilinear halo-orbit was discovered as a kind of bridge between the halo L₁ and L₂ in the Earth-Moon system. Since then, many studies have studied the use of the Near-Linear Halo-Orbit for use in various concepts of the exploration of the Moon, including the constant coverage of the South Pole. NRHOs are halo orbits with large amplitudes over the north or South Pole with shorter periods that pass close to the opposite pole. Although they look like large elliptical orbits, they are CR3BP orbits that remain relatively stationary in the Earth-Moon plane, rotating at the same speed as the Moon around the Earth and the Moon around its own axis \[3, 8\].

If we specifically place the satellite at point L₂ without speed, it will rotate together with point L₂. The white trajectory in fig. is the trajectory of the satellite, which is fixed relative to the point L₂ with the influence of the Sun. It is obvious that no more than one turn, it will fly to the sun.

The numerical solution of the orbital motion is carried out in special software.
In the system of central gravity of the Earth (Fig. 4) it is seen that the satellite rotates around the Earth with a period of 28 days, it will fly no more than one turn, this means that the trajectory is high unstable.

4.1. Analysis of Halo orbit at libration point

If the satellite is not stationary, but rotates around the point L₂, then the trajectory is halo-orbit, the period is 8-14 days. In the central gravity system of the Moon, it can be seen that the satellite simultaneously rotates around the Moon, and around the L₂ point in the Earth-Moon rotating system, also around the Earth, in the central gravity system of the Earth (in fig.5).

The numerical solution of the orbital motion is carried out in special software.

The halo orbit is slightly more stable than the fixed satellite at the point L₂, but even the initial velocity changes fractionally, the halo orbit does not work. See in fig. 6a, 6b.
4.2. Analysis of Near Rectilinear Halo Orbits

Influenced by the Moon, the Earth and the sun, it is unstable. From the point of view of the Moon, the DSG repeatedly passes one pole, providing great opportunities for scientific measurements.

| Coordinates | Value      |
|-------------|------------|
| X           | 67000 km   |
| Y           | 0 km       |
| Z           | 2200 km    |
| Vx          | 2 km/s     |
| Vy          | 0.6 km/s   |
| Vz          | 0 km/s     |
As can be seen in Fig. 8, the height of the apolune is 55000 km ÷ 70000 km, the height of perilune is almost 2000 km ÷ 3000 km. After some time they will lead away if without correction.

In the Earth-Moon rotary system, the trajectory is a more stable ellipse. This means that the spacecraft is always oriented toward the Earth.

In the system of central gravity of the Earth in Fig.10, it is apparently symmetrical with a period of 6-8 days. NRHO with a period of 6.83 days will have a period equal to 1/4 of the lunar sidereal day. Thus, the geometry of the orbit would repeat every lunar orbit. This can make predictable rendezvous graphics more achievable.
5. Conclusion

Studies of the orbit show that these orbits are only quasistable, therefore, to maintain the DSG in these orbits will require some adjustments to the DSG position. The orbits to be used for the DSG mission have advantages and disadvantages. Namely:

The halo orbit at $L_2$ in the Earth-Moon system shows a good gain in the velocity increment $\Delta V$. However, the remoteness of this orbit from the surface of the Moon is its disadvantage, since it will take a lot of time to fly from this orbit on the surface of the Moon.

For the NRHO orbit, its closer position to the Moon can be distinguished, the flight time is reduced accordingly, but its configuration makes it necessary to constantly recalculate the position of the spacecraft in orbit.

As a result, the main conclusion can be made: the DSG mission provides a great scientific interest, opens up opportunities for exploring the Moon and other planets of the solar system.

The orbital motion for DSG is rather complicated, and it is necessary to study this issue in detail!

References

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