Analysis of the transfer trajectory from the moon to the Halo orbit for the small scientific spacecraft (DESTINY)

深宇宙探査技術実験ミッション DESTINY における 月軌道からハロー軌道までの遷移軌道の解析

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This study investigates the trajectory design of the small scientific spacecraft, DESTINY (Demonstration and Space Technology for INterplanetary voYage), which aims to be launched by the third Japanese next-generation solid propellant rocket (Epsilon rocket) around 2017. In the DESTINY mission, the spacecraft will go to the moon by the ion engine from the large ellipse orbit. Afterward, by using the lunar swing-by, the spacecraft will put into the periodic orbit in the vicinity of the libration point (Halo orbit) of the Sun- Earth L2. This study focuses on the transfer trajectories from the moon to the Halo orbit.

1. Introduction

DESITINY (Demonstration and Experiment of Space Technology for INterplanetary voyage) is the engineering small satellite for deep space exploration, which aims to be launched by the third Japanese next-generation solid propellant rocket (Epsilon rocket) around 2017 [1].

In the DESTINY mission, spacecraft is put into the elliptical orbit of 200 x 24000 km by the Epsilon rocket firstly. Subsequently the apogee altitude is increased to the moon orbit by the high specific ion engine, after that, the spacecraft transfers to the Halo orbit in the vicinity of the Lagrange point of the Sun-Earth. This paper focuses on the later part, the transfer from the moon to the Halo orbit.

There has been great interest in the Halo orbits of the Sun-Earth system, which are located where the gravity of the Sun and Earth and centrifugal force acting on the spacecraft are balanced. The Halo orbit is considered as a notable location for astronomical observatories. It is because an object around these place can maintain the same orientation with respect to the Sun and Earth, thus it is easy to shield the telescope from the heat source like the Sun and Earth. In fact, starting with the ISEE-3 (International Sun–Earth Explorer-3) launched in 1978, several astronomical satellites such as the Genesis, WMAP, Herschel, and so on have already utilized such locations by the American and European agency, NASA and ESA [2]. In future, astronomical observatories like the JWST (James Webb Space Telescope) and GAIA will likely be located near the Sun Earth L2 point [3]. The Japanese space agency (JAXA) is planning its libration point mission, SPICA (Space Infrared Telescope for Cosmology and Astrophysics), to be launched into the Sun-Earth L2 Halo orbit [4].

In general for the transfer from the Earth to the Halo orbit, the stable manifold, which is the eigenstructure associated with the Halo orbit, is utilized because it reduces the required delta-V and allows us to avoid the critical operation of the insertion maneuver to the Halo orbit at the cost of the time of flight [5, 6] (Fig. 1). In this study, the stable manifold is used for the transfer from the moon to the Halo orbit in a similar way. First we investigate the characteristic of the stable manifold around the moon orbit. And then, the connectivity between the moon and the stable manifold is analyzed.

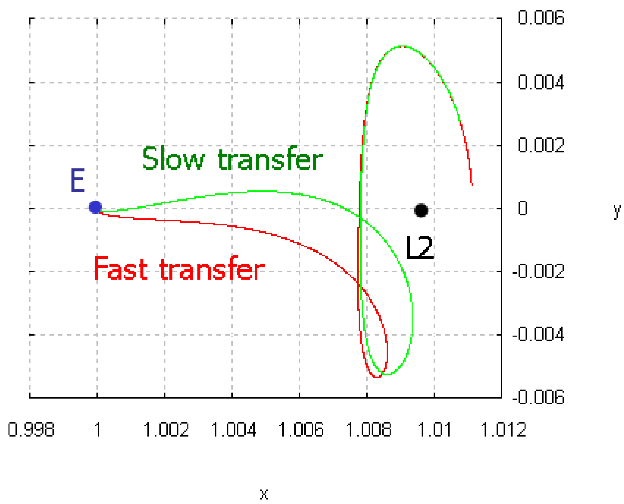

Fig. 1: Transfer Trajectory to the Halo Orbit Using the Stable Manifold [4]

2. DESTINY MISSION

2.1. Overview

The objective of the DSTINY mission is to acquire the key technologies and skills of the future deep space exploration. The following seven engineering experiments will be conducted in the DSTINY mission.

(1) High energy orbit injection by Epsilon rocket
(2) Thin-film lightweight solar panel
(3) Large-scale ion engine
(4) Orbital determination under low thrust operation

(5) Advanced thermal control
(6) Automatic/autonomous onboard operation
(7) Halo orbit transfer and maintenance

This study targets at the (7) experiment, and this skill is likely to use the future Japanese Lagrange point mission, SPICA.

2.2 Mission Design

For the nominal plan, spacecraft is put into the highly elliptical orbit by the Epsilon rocket firstly. Subsequently the apogee altitude is increased to the attitude of the lunar orbit by the ion engine, after that, the spacecraft transfers to the Halo orbit of Sun-Earth L2 by lunar swing-by, and orbit maintenance is planed for about one year (close to the two periods of the Halo orbit). For the extended mission, putting into the Earth-Moon Halo orbit and maintaining/leaving its orbit, and/or returning to the Earth from the Halo orbit are covered. In this study, the transfer from the moon to the Halo orbit, the later stage of the nominal mission, is investigated (see Fig. 2).

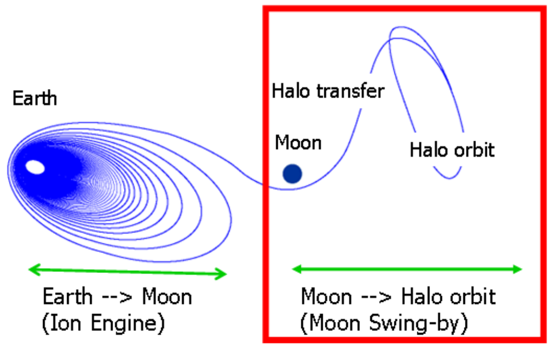

Fig. 2: Trajectory Design in DESTINY Mission.

3. DYNAMICAL MODEL

3.1 Equations of Motion

Since this study treats the transfer from the moon to the Sun-Earth Halo orbit, the JPL ephemeris date (DE405 [7]) of the Sun, Earth, and Moon are used for spacecraft motion. In this motel, the equation of motion is expressed by

$$\frac{d^2\boldsymbol{r}}{dt^2} = -\frac{\mu}{r^3}\boldsymbol{r} + \sum_{k=1}^{n}\mu_k\left(\frac{\boldsymbol{r}_k-\boldsymbol{r}}{\left|\boldsymbol{r}_k-\boldsymbol{r}\right|^3} - \frac{\boldsymbol{r}_k}{r_k^3}\right) + \ddot{\boldsymbol{r}}_{SRP} \qquad (1)$$

where $\boldsymbol{r}$ is the distance from spacecraft to the Sun, $\boldsymbol{r}_k$ is the distance from spacecraft to the Earth/Moon, and μ_k is the gravitational parameter of the Sun, Earth and Moon.

3.2 Lagrange Points

Libration points of the Sun-Earth system, called Lagrange points, are located where the gravity of the Sun and Earth and centrifugal force acting on the spacecraft are balanced (Fig. 3). In particular, the position of L1 and L2, which lie on the line connecting the Sun and Earth, are considered as a notable location for astronomical observatories. The Japanese space agency (JAXA) is planning its first libration point mission, SPICA (Space Infrared Telescope for Cosmology and Astrophysics), to be launched into the Sun-Earth L2 Halo orbit.

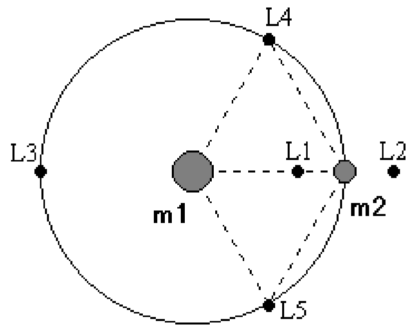

Fig. 3: Lagrange Points

3.3 Halo Orbits and Stable Manifold

There exist three-dimensional periodic orbits near the L1 and L2 points called Halo orbits [8-12]. If a spacecraft is placed on a Halo orbit about the L2 point, it will be not hidden inside the shadow of the Earth because the radius of the Halo orbit can be made larger than that of the Earth.

Moreover there exist invariant structures associated with the Halo orbit, called stable manifolds [13-17] (see Fig. 4). These are trajectories that wind onto the Halo orbit naturally. We exploit the stable manifolds for the transfer to the Halo orbit.

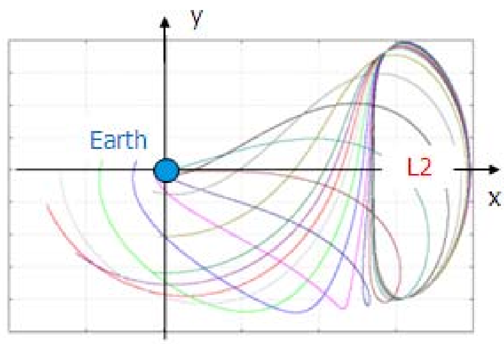

Fig. 4: Halo Orbit and Stable Manifold

4. TRANSFER TRAJECTORY TO HALO ORBIT UTILIZING THE STABLE MANIFOLD

In general, the stable manifold is used for the transfer from the Earth to the Halo orbit. In this study, the availability of the stable manifold for the transfer from the Moon in a similar way is investigated.

4.1 Characteristic of the Intersection of the Stable Manifold with the Ecliptic Plane

First, the characteristic of the stable manifold around the moon orbit is investigated. In this study, suppose that the plane of the moon's orbit is identical to the ecliptic plane, but actually they are slightly different.

Fig. 5 shows the first to fourth intersect points of the stable manifold propagating backward in time from the Halo orbit at the Ecliptic plane. From this figure, we can say that the stable manifold tube has four intersections to the moon orbit.

Fig. 6 plots the distance of the intersections from the geocentric against the time of flight (TOF) from the Halo orbit in backward. The TOF from the Halo is around 230 days for any four cases, and we assume that the investigation until the fourth intersection would suffice for the transfer from the moon to the Halo orbit because the fifth and more intersections would take the long TOF.

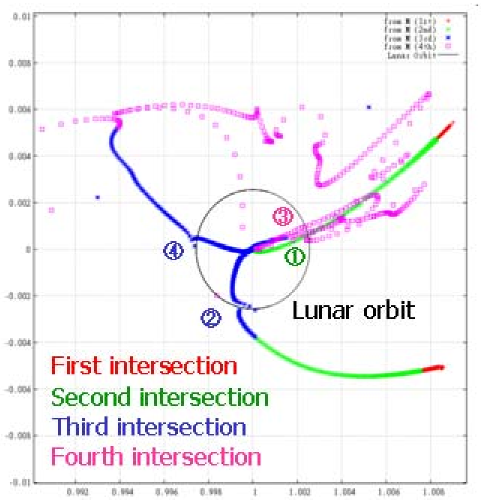

Fig.5: Intersection between the Stable Manifold and the Ecliptic Plane

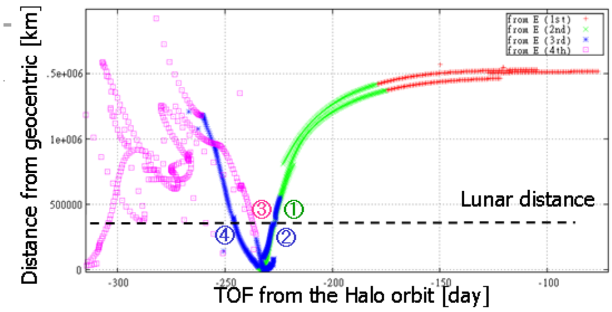

Fig.6: Relation between the Distance from the Geocenter and TOF in Backward

4.2 Transfers from the Moon to the Halo Orbit

Based on the results in the previous section, Fig. 7 represents the transfer trajectories to the Halo orbit from the above-mentioned four intersections. Moreover, Table 1 shows the relative velocity of the stable manifold to the moon and the transfer time for each intersection. As a result, the stable manifold intersects to the moon orbit tangentially for the case 2 and 4, and intersects orthogonally for the case 1 and 3. Thus, since the relative velocity for the case 2 and 3 are relatively small, around 400 m/s, these two trajectories are candidates for the transfer to the Halo orbit..

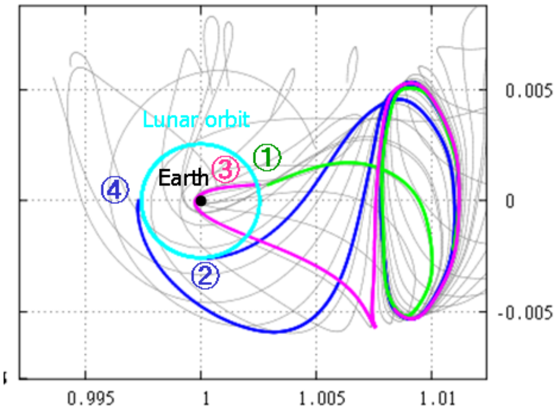

Fig.7: Transfer trajectories from the moon to the Halo orbit

Table 1: Orbit Correction by FTA [m/s]

Intersection	ΔV to Moon [m/s]	TOF [day]
1	1390	227
2	400	226
3	1520	237
4	420	245

CONCLUSIONS

In this paper the transfer trajectories from the moon to the Halo orbit for the DESTINY mission is studied.

Assuming the usage of the stable manifold for the transfer from the moon, the characteristic of the intersection of the stable manifold at the ecliptic plane was investigated. As a consequence, there are four intersections to connect the moon orbit. Furthermore, it was found that the relative velocity of the stable manifold at the intersections is at least 400 m/s, and the time of flight from the moon to the Halo orbit is approximately 230 days.

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