Element Technologies for Trajectory Design for Lunar/Planetary Exploration

TERADA Hiroshi, MATSUOKA Masatoshi, TANAKA Kimie, UKAI Chiaki

Abstract

Trajectory design for lunar/planetary probes requires technologies different from those required by Earth-orbiting satellites. NEC has long been in charge of trajectory design for many lunar and planetary probes in cooperation with the Japan Aerospace Exploration Agency (JAXA) and its predecessor organization. This paper gives an outline of the main technology elements involved and the trajectory design characteristics of various projects based on them.

Keywords

trajectory design, lunar/planetary probe, swing-by, launch window
electrical propulsion, planetary exploration, lunar exploration

1. Introduction

The return to Earth of the MUSES-C (HAYABUSA) asteroid probe on June 13, 2010 became a popular topic in Japan. The MUSES-C overcame a large number of incidents before its return, and it was necessary to review its trajectory design after every incident. What made these reviews of the trajectory design possible was our accumulation of experience and technology cultivated through more than two decades of trajectory design for lunar and planetary probes since the MUSES-A (HITEN) lunar probe launched in 1990.

Trajectory design lasts from the probe concept study stage through to the completion of the mission after the launch and plays a critical role in any lunar/planetary probe project.

2. Outline of Technology Elements

(1) Launch window design

Needless to say, the target of a lunar/planetary probe is a celestial body other than the Earth (Moon, Mars, etc.). Since the target celestial body is also in orbital motion, if the timing of the rendezvous with the target body in space is not correct, a period of a few months to a few years is necessary until a re-encounter for another try. Consequently, the design of the launch window (the date, time and direction of launch of the probe's launch vehicle) should be calculated with high precision by considering the changes over time of the locations of the Earth and the target celestial body. Since both the time and direction of launch need to be different depending on the launch date, the design is much more complicated than it is for Earth-orbiting satellites.

Fig. 1 shows a schematic of a trajectory to the Moon. The spacecraft temporarily enters an Earth orbit, called the parking orbit, after launch. It is difficult for the probe to reach the Moon if the Moon at the time of arrival is not located on the plane formed by the vector of the spacecraft's velocity direction and the center of the Earth (the parking orbit plane). Fig. 1 shows a case in which the parking orbit plane has deviated from the location of the Moon at the time of arrival due to a too-early launch time. However, if the carrier rocket is launched slightly later, the parking orbit plane and the location of the Moon at the time of arrival will match, thanks to the Earth's rotation, and the probe will be able to arrive at

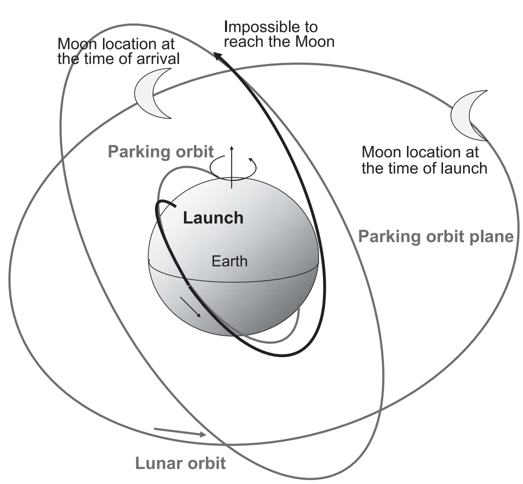

Fig. 1 The launch window concept (1).

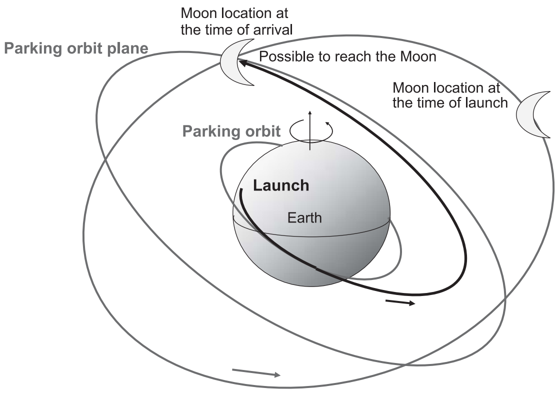

Fig. 2 The launch window concept (2).

the Moon (**Fig. 2**).

In fact, since the lunar orbit is elliptical, it is also necessary to consider that a change in launch time results in a change in the time until arrival. As described above, the launch window should be designed with four-dimensional calculations, considering the time domain in 3D space.

(2) Swing-by

A swing-by (SWB) is a technique for changing the trajectory of a probe without using the propellant in the probe by utilizing the gravity and orbital motion of a celestial body. Executing a SWB several times, with repeated accelerations and decelerations, makes it possible to maintain a target orbit for a long time.

In **Fig. 3** , an orbit with an apogee near the Moon (about a 14-day period) is converted by a SWB (acceleration) to an orbit with about a 40-day period, and when the probe returns to the lunar orbit in a few more than 30 days, the orbit is reconverted by a second SWB (deceleration) to an orbit with an apogee altitude similar to that of the initial orbit.

These two SWB maneuvers change the apogee direction as seen from the Earth by a few tens of degrees. When this is synchronized with the sunward motion caused by the Earth's rotation, it is possible to place the probe's apogee permanently on the night side of the Earth and to continue observations in that area for a long period. In addition, the apogee distance (altitude) can also be varied by changing the SWB conditions (minimum distance and angle). Meanwhile, when repeated SWB maneuvers are planned, it is necessary to design the conditions for the first SWB in order to make the second SWB possible.

As seen typically with this example of SWB, correct orbit design calculations in deep space are no longer possible by

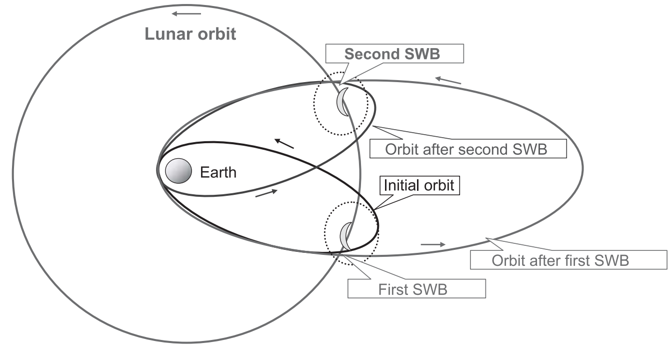

Fig. 3 Concept of a double lunar SWB.

simply using Kepler's laws, as the gravity of the Moon, Sun and other planets must be taken into consideration in addition to the gravity of the Earth. This is one of the most important characteristics of trajectory design for lunar/planetary probes.

(3) Trajectory design using electrical propulsion

Electrical propulsion produces a lower thrust force than does chemical propulsion, but its advantage is that it has about 10 times greater fuel efficiency.

This means that, for instance, a maneuver that requires 100 kg of fuel with traditional chemical propulsion is possible with 10 kg of fuel using electrical propulsion. This is a great advantage of this method.

On the other hand, a probe using chemical propulsion is able to change its orbit by exerting an impulse-type propellant force, but one with electrical propulsion requires a longer period of propellant force exertion for the same amount of orbit change, which complicates the calculations for electrical propulsion. Furthermore, electrical propulsion needs to obtain the optimum solution under multiple restrictions, including those on attitude and thrust force due to the need for communication with the ground and the use of electrical power.

3. Outline of Projects

Since the MUSES-A (HITEN) launched in 1990, NEC has been in charge of trajectory design for almost all the lunar/planetary probes developed in Japan (see **Table**). Although the GEOTAIL is not exactly a probe for exploration of the Moon or a planet, it is listed in the following table because it employs trajectory design technologies similar to those of other probes.

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Table Lunar/planetary probes with trajectory design developed by NEC.

Name	Launch Date (Vehicle)	Target Trajectory Properties
MUSES-A (HITEN)	Jan. 24, 1990 (M-3SII)	Double lunar swing-by, aerobraking, Lagrange point orbiting, lunar orbit insertion, controlled hard landing on the Moon
GEOTAIL	July 24, 1992 (Delta II)	Double lunar swing-by
PLANET-B (NOZOMI)	July 4, 1998 (M-V)	Lunar/Earth swing-by Mars orbit insertion
MUSES-C (HAYABUSA)	May 9, 2003 (M-V)	Electrical propulsion, Earth swing-by, approach to Asteroid 25143 ITOKAWA, pinpoint landing, return to Earth
SELENE (KAGUYA)	Sep. 14, 2007 (H-IIA)	Lunar orbit insertion/maintenance, controlled hard landing on the Moon
PLANET-C (AKATSUKI)	May 21, 2010 (H-IIA)	Venus orbit insertion

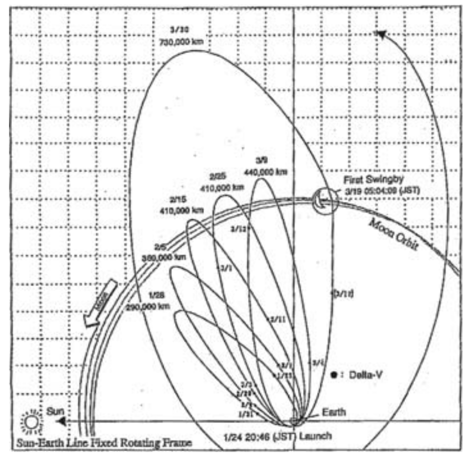

Fig. 4 Trajectory of the MUSES-A (from launch to SWB1) (Sun-Earth line fixed rotating coordinate system).

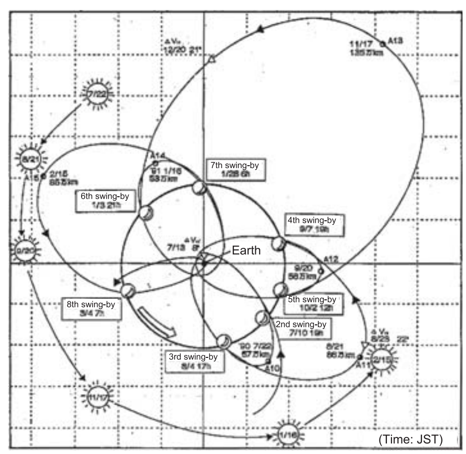

Fig. 5 Trajectory of the MUSES-A (Inertial coordinate system).

(1) MUSES-A (HITEN)

The MUSES-A (HITEN) was a probe whose mission was to acquire orbit control techniques indispensable for future lunar/planetary probes, including SWB.

After its launch, the MUSES-A orbited the Earth five and half times, then performed a lunar SWB (**Fig. 4**) and inserted a subsatellite (named HAGOROMO) into a lunar orbit. As the subsatellite did not have an attitude control subsystem, the orbit insertion was designed so that its attitude at the time of separation from the MUSES-A coincided with the direction of acceleration for the orbit insertion.

After moving the apogee to the side opposite to the Sun, double lunar SWBs were executed continuously to acquire the SWB techniques to maintain the probe on the opposite side of the Sun for a long period. The resulting orbits feature an orbital diagram like flower petals in the inertial coordinate system (**Fig. 5**).

After the above, an aerobraking experiment using the Earth's atmosphere and entry to a Lagrange point orbit were conducted, and then the MUSES-A entered a lunar orbit and was finally put to a controlled hard landing on the Moon's surface at a time in which it was visible from Japan on April 11, 1993.

(2) GEOTAIL

The GEOTAIL's mission was to maintain a probe on the Earth's magnetotail (in the direction opposite to the Sun) for a long period for observation by using the SWB techniques acquired with the MUSES-A. **Fig. 6** shows the various orbits entered by its 14 planned and executed SWB maneuvers. **Fig. 7** is an expression of the same orbits in the Sun-Earth line fixed rotating coordinate system, which is dependent on the motion of the Sun. It indicates that the apogees are always in the direction opposite to the Sun and that they cover a wide range, as far as 1.4 million km from the Earth.

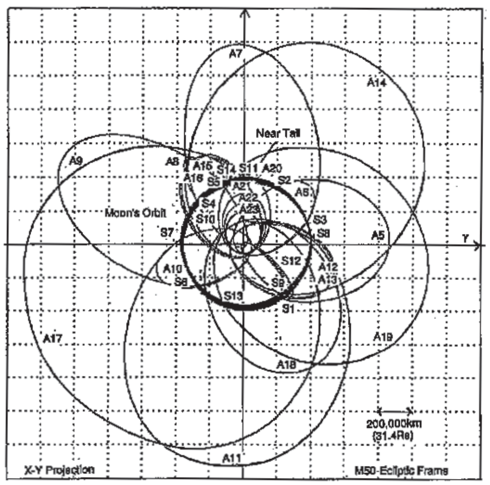

Fig. 6 Trajectory of the GEOTAIL (Inertial coordinate system).

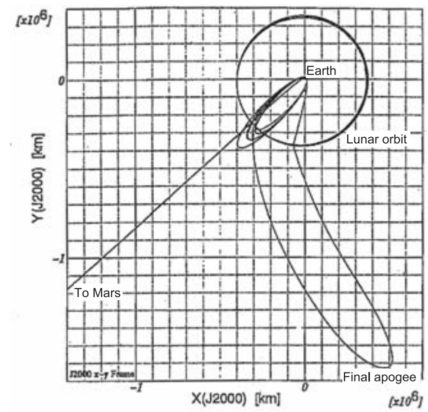

Fig. 8 Trajectory of the PLANET-B (Until escape from Earth's gravitational sphere).

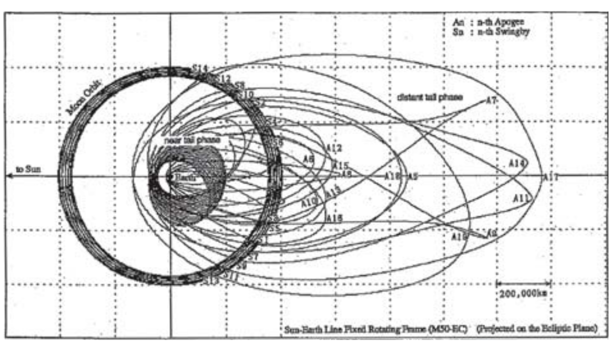

Fig. 7 Trajectory of the GEOTAIL (Sun-Earth line fixed rotating coordinate system).

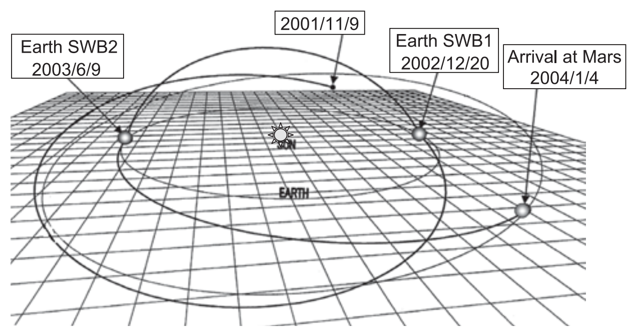

Fig. 9 Trajectory of the PLANET-B (Earth to Mars).

(3) PLANET-B (NOZOMI)

With the PLANET-B (NOZOMI) Mars probe, a double lunar SWB was used in a way different from those of the MUSES-A and GEOTAIL (**Fig. 8**). Double lunar SWBs had previously used an acceleration SWB and a deceleration SWB as a set, but the PLANET-B's double lunar SWB was designed to use acceleration SWBs in both maneuvers in order to reduce the amount of acceleration needed to travel from the Earth to Mars.

To our regret, the PLANET-B failed to enter a Mars-bound trajectory due to engine trouble, but we re-established a plan to arrive at Mars in 2004 by performing two Earth SWBs (**Fig. 9**).

(4) MUSES-C (HAYABUSA)

The biggest feature of the trajectory design for the MUSES-C (HAYABUSA) asteroid probe was its use of an

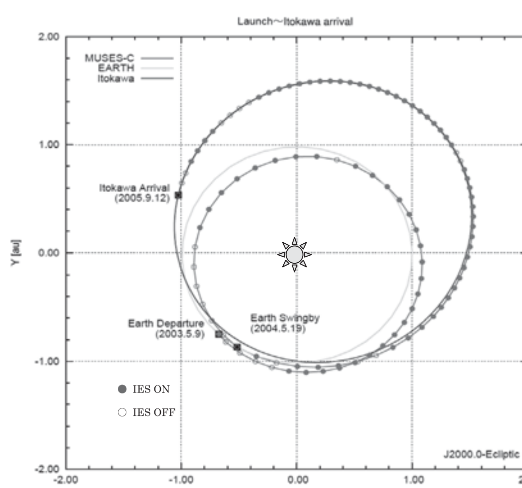

Fig. 10 Trajectory of the MUSES-C (Outward flight).

electrical propulsion system. On its outward flight toward Asteroid 25143 ITOKAWA, we succeeded in changing its trajectory drastically by means of an Earth SWB (**Fig. 10**). On its return flight, we were able to pioneer a new trajectory design technique, which was pinpoint entry to the Earth (Australia).

(5) SELENE (KAGUYA)

The SELENE (KAGUYA) lunar orbit spacecraft featured insertion into a low-altitude lunar orbit and maintenance of orbit altitude. Its insertion into a lunar orbit at 100 km altitude was divided into six maneuvers for the sake of efficiency and the separation of subsatellites Rstar (OKINA) and Vstar (OUNA).

Considering the non-uniform distribution of lunar gravity, we also established a plan to perform a maneuver every two months to correct the resulting deviation from the initial orbit (**Fig. 11**).

On June 11, 2009, a controlled hard landing of the SELENE on the lunar surface was performed at a time in which it was visible from Japan like the MUSES-A had been.

(6) PLANET-C (AKATSUKI)

Because the launch vehicle of the PLANET-C (AKATSUKI) Venus Climate Orbiter was intended to be injected directly into a Venus-bound orbit, what was important in its trajectory design was to strictly define the orbit into which the launch vehicle would be inserted. The actual launch was performed with almost no orbit insertion error, so that little orbital correction was required in-flight. **Fig. 12** shows the Venus transfer orbit of the PLANET-C.

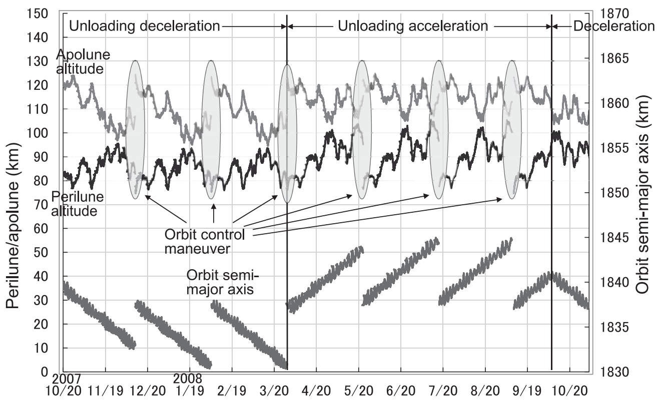

Fig. 11 Altitude change and orbit control of the SELENE.

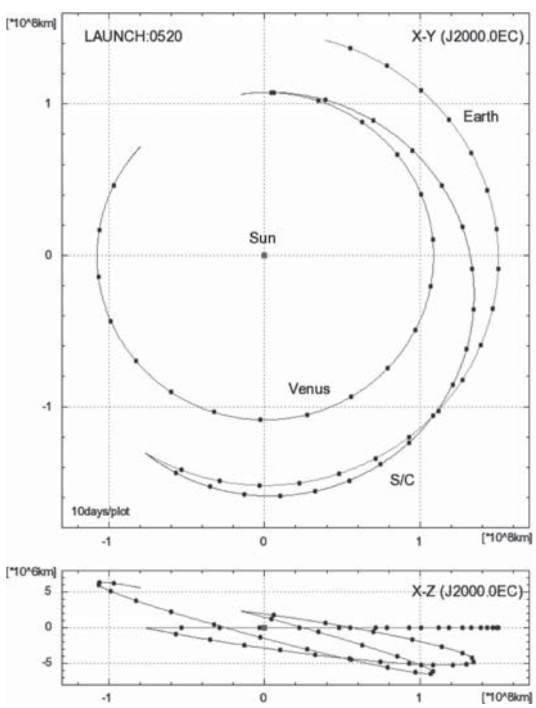

Fig. 12 Venus transfer orbit of the PLANET-C.

4. Conclusion

We have established the trajectory plans of a large number of lunar and planetary probes and have accumulated much expertise through orbit control operations. We are determined to design accurate, efficient trajectory plans for the lunar and planetary probes to be developed in the future.

In closing this paper, we would like to express our deep gratitude toward the people of JAXA for their guidance.

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