Analysis of Interplanetary Transfers between the Earth and Mars Halo orbits

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Spacecraft interplanetary transportation systems using Earth and Mars Halo orbits are analyzed. This application is motivated by future proposals to place “deep space ports” at the Earth and Mars Halo orbits as space hub for planetary Mission. First, the feasibility of interplanetary trajectories between Earth Halo orbit and Mars Halo orbit was investigated, and such trajectories were designed with reasonable DV and flight time. Here, we utilize unstable and stable manifolds associated with the Halo orbit to approach the vicinity of the planet’s surface, and assume impulsive maneuver for escape and capture trajectories from/to Halo Orbits. Next, applying to Earth-Mars transportation system using spaceports on Halo orbits, we evaluated the system with respect to the mass of round-trip transfer. As a result, the transfer between the low Earth orbit and the low Mars orbit via the Earth Halo orbit and the Mars Halo orbit could be saved the fuel cost compared with a direct transfer between the low Earth orbit and the low Mars orbit.

1. INTRODUCTION

These days there has been great interest in the libration points of the circular restricted 3-body problem (CR3BP), where the gravity of the primary and secondary bodies and centrifugal force are balanced. In particular, the position of L1 and L2, which lie on the line connecting the two bodies, can be considered equivalent to the boundary of the gravitational dominance of the secondary body. Since an object around these points can maintain the same orientation with respect to the two bodies, transfers between the primary body and the libration point have been investigated extensively in the past1-6. In fact, several astronomical satellites have already utilized such Halo orbits around the L1 and L2 points of the Sun-Earth system7, and future astronomical observatories like JWST will likely be located near the Sun-Earth L2 point requiring human servicing and repair. Moreover, transfers to the inner or outer planet region from the vicinity of the Sun-Earth L1 and L2 are relatively simple by addition of energy to a spacecraft. Therefore, these points are also considered as candidate gateways for interplanetary transfers in the future8-13. Recently, the analysis and design of transfer orbits using invariant manifolds associated with Halo orbits have been a topic of study14-20.

Furthermore, if spaceports are built around not only the Sun-Earth but Sun-Target planet L1/L2 points, we can separate the transportation system into three regions: transfer inside the gravity field of the Earth, transfer inside the gravity field of a target planet, and the interplanetary transfer phase as shown in Fig. 1. Moreover, assuming that propellants are left at these spaceports on the way to the target planet, the mass of spacecraft could be reduced. Thus, this system facilitates round-trip exploration using spaceports as relay points and leads to a reusable transportation system8,11. In the past, the escape trajectories from the libration points of Sun-Earth system also have been examined21,22. However, capture trajectories to Halo orbits of target bodies from interplanetary transfers, and also interplanetary transfers between Halo orbits are not fully understood.

In the previous symposium, we investigated the capture trajectories to Halo orbit from interplanetary transfers. In this study, interplanetary transfers between Halo orbits are investigated. Besides, an application to Earth-Mars transportation system using spaceports at Earth and Mars Halo orbits is discussed.
2. HILL THREE-BODY MODEL

The physical system considered in this paper is the restricted Hill three-body model. This model is a limiting case of the circular restricted three-body problem (CR3BP) and describes the dynamics of a massless particle attracted by two point masses revolving around each other in a circular orbit (see Fig. 2). In fact, the Hill model can be obtained from the CR3BP by setting the center of the coordinate system to be at the secondary body and then assuming that the distance of the satellite from the center is small compared to the distance between the target body and the sun. The resulting equations of motion provide a good description for the motion of a spacecraft in the vicinity of the L1 and L2 libration points of the smaller body.\textsuperscript{23}

2.1 Equations of Motion

The normalized equations of motion for spacecraft in this Hill model are given by\textsuperscript{24,25},

\begin{align}
\ddot{x} - 3 \dot{y} - 3x &= -\frac{x}{r^3}, \\
\ddot{y} + 2 \dot{x} &= -\frac{y}{r^3},
\end{align}

Figure 1: Vision of an Interplanetary Transfer in the Future

Figure 2: Geometry of the Restricted Hill Three-Body Model
\[
\ddot{z} = -z - \frac{z}{r^3},
\]

where \( r = \sqrt{x^2 + y^2 + z^2} \) is the distance from the center of second smaller body to a spacecraft. There are no free parameters in these equations. Thus, computations performed for them can be scaled to any physical system by multiplying by the unit length and time, \( l = (\mu/\omega_0)^{1/3} \) and \( \tau = l/\omega_0 \), which only depend on the properties of the primary and secondary bodies (\( \omega_0 \) is the angular velocity of the secondary body about the primary body, and \( \mu \) is the gravitational parameter of the secondary body).

### 2.2 Libration Points

In the restricted Three-body problem model there are five equilibrium points where the gravity of the first and second massive bodies and centrifugal force acting on S/C are balanced, called libration points. In the restricted Hill Three-body problem only the L1 and L2 libration points exist, and they are symmetric about the origin with coordinates \( x = \pm (1/3)^{1/3} \approx \pm 0.693... \), \( y = 0 \), \( z = 0 \).

### 2.3 Jacobi Integral

Equations (1)-(3) have an integral of motion similar to the CR3BP. The following equation denotes the Jacobi integral, which is a conservative quantity determined from the initial conditions,

\[
J = \frac{1}{2} v^2 - \frac{\mu}{r} + \frac{3x^2}{2}
\]

where \( v = \sqrt{x^2 + y^2 + z^2} \) is the velocity of the particle in the rotating frame. This constant has a deep influence on the dynamics of motion. The condition \( v^2 \geq 0 \) in Eq. (4) impose a restriction on the allowable position for the motion at any given the value of \( J \). Setting \( v = 0 \) defines the zero-velocity surface, which sets a physical boundary of the allowable motion. In particular, the critical value of \( J \) at L1 and L2 defines the energy at which the zero-velocity surfaces open at L1 and L2, and is expressed as

\[
J_{L1,2} = \frac{1}{2} 9^{2/3} = 2.16337...
\]

Table 1 gives the normalized radius for most planets of the solar system.

<table>
<thead>
<tr>
<th>Planet</th>
<th>Mass ((\times 10^{-23} \text{ kg}))</th>
<th>Gravitational parameter ((\times 10^5 \text{ km/s}^2))</th>
<th>Mean motion ((\text{rad/s}))</th>
<th>Normalized radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.3302</td>
<td>0.220329</td>
<td>8.27 (\times 10^{-7})</td>
<td>0.007663</td>
</tr>
<tr>
<td>Venus</td>
<td>4.869</td>
<td>3.248889</td>
<td>3.24 (\times 10^{-7})</td>
<td>0.00415</td>
</tr>
<tr>
<td>Earth</td>
<td>5.9742</td>
<td>3.968345</td>
<td>1.99 (\times 10^{-7})</td>
<td>0.002955</td>
</tr>
<tr>
<td>Mars</td>
<td>0.61911</td>
<td>0.428321</td>
<td>1.06 (\times 10^{-7})</td>
<td>0.002173</td>
</tr>
<tr>
<td>Jupiter</td>
<td>1899</td>
<td>1267.127</td>
<td>1.68 (\times 10^{-8})</td>
<td>0.000933</td>
</tr>
<tr>
<td>Saturn</td>
<td>588.8</td>
<td>379.5375</td>
<td>6.76 (\times 10^{-9})</td>
<td>0.000841</td>
</tr>
<tr>
<td>Uranus</td>
<td>86.86</td>
<td>57.9582</td>
<td>2.67 (\times 10^{-9})</td>
<td>0.000253</td>
</tr>
<tr>
<td>Neptune</td>
<td>102.4</td>
<td>68.32742</td>
<td>1.21 (\times 10^{-9})</td>
<td>0.000148</td>
</tr>
</tbody>
</table>
2.4 Halo Orbit and Invariant Manifolds

In addition, there exist periodic orbits near the libration points in three-dimensional space called Halo orbits\(^{26-30}\), respectively, whose sizes depend on the value of the Jacobi constant.

These Halo orbits are not stable completely. There exist invariant structures associated with Halo orbits, called unstable and stable manifolds (see Fig. 3). These are very sensitive and are affected by initial conditions. We exploit this stable manifold for capture trajectories to periodic orbits around the libration points.

![Fig. 3: Stable Manifold around L1 (Until first Periapsis Points)](image)

3. ESCAPE AND CAPTURE TRAJECTORIES FROM/TO HALO ORBITS

3.1. Assumption of Escape and Capture Trajectories

In this study, we assume that escape trajectories are trajectories that leave from Halo orbits of Sun-Earth L1 or L2 using unstable manifolds and approach the Earth. Subsequently, at closest approach an impulsive maneuver is performed to escape from the Earth’s gravitational dominance and to put the spacecraft on interplanetary trajectories. The reason why an impulsive maneuver is performed near the surface of the Earth (perigee) is because it is the energetically most efficient place to increase the escape energy.

On the other hand, we assume that capture trajectories are trajectories that enter the sphere of influence of a target body after interplanetary transfer and have a close flyby to the target body. And then, at closest approach for the target body, an impulsive maneuver is performed to put the spacecraft on stable manifolds that lead to capture to Halo orbits of the target body. The reason why an impulsive maneuver is performed near the surface of the target body (periapsis) is because it is the energetically most efficient place to reduce the approach energy, which may also be reduced by using an aero assist with the planetary atmosphere. After orbiting around the target body a few times, the S/C is finally placed into Halo orbits. At this time, an infinitesimal impulsive maneuver is necessary to insert onto the Halo orbit completely, but it is negligible. In this way, the unstable and stable manifolds are used for escape and capture trajectories from/to Halo orbits.

3.2. Characteristics of Periapsis Points of Invariant Manifolds

First, we investigate the first four periapsis passage points of unstable/stable manifolds, where an impulsive maneuver may be performed to escape from Halo orbits of the Earth and to capture into the Halo orbits of the target body, propagated from certain points on the Halo orbits in forward/backward. Here, these locations of periapsis point of unstable and stable manifold are symmetric to the y = 0 plane. Besides, the periapsis locations of L1 and L2 stable manifolds are symmetric to the x = 0 plane. Therefore, we mainly discuss the results of periapsis of L1 stable manifolds here. Fig. 4 shows an example of the first four periapsis passage points of one example trajectory of the L1 stable manifold (in the planar case for J = -2.15). The secondary body is located at the origin. Based on this result, it was found that the first four periapsis point locations of the L1 stable manifold vary with the value of the Jacobi constant (i.e., the size of Halo orbits)\(^{31}\).

Moreover, we have obtained that the relation between minimum periapsis distances and the value of the Jacobi constant\(^{31}\). The minimum periapsis distance means the distance from the origin to the periapsis point of stable manifold, which is closest to the origin in each of four periapsis points in the same value of the Jacobi constant. Each four minimum periapsis distance becomes smaller than 0.000148 (which is smaller than the smallest normalized planetary radius, Neptune) when the value of the Jacobi constant is changed. Thus the stable manifolds of first four periapsis passage points can intersect the
surface of any of the planets in the solar system. Therefore, stable and unstable manifolds could be used for escape and capture phases from/to Halo orbits.

![Graph showing first four periapsis passage points of a trajectory of the stable manifold propagated backward for J = -2.15][31].

3.3. Reduction of Time of Flight for Escape and Capture from/to Halo orbit

Although we found that the impulsive maneuver could be performed at the surface of any of the planets in the solar system using the unstable and stable manifolds, the time of flight (TOF) becomes long for our escape and capture on the Halo orbit using the unstable and stable manifold because the manifolds generally orbit around the L1/L2 point several times. For instance, the TOF is approximately 1.9 years for the capture using stable manifold from Mars periapsis to the arrival point on the Halo orbit. Thus, a reduction of the TOF for the escape and the capture was discussed in the previous symposium. To reduce TOF for escape and capture, we assume performing $V_{\text{peri}}$ and $V_{\text{HO}}$ at both the periapsis of manifold and the point on Halo orbit, respectively. As a result, TOF could be reduced more than a year by performing a $\Delta V$ of only 0.06 km/s. It is a significant improvement by performing a decent $\Delta V$. Moreover, it was found that TOF has a linear relation with the logarithm of the minimum required $\Delta V$.

4. ANALYSIS OF LINKING INTERPLANETARY TRAJECTORIES WITH THE STABLE/UNSTABLE MANIFOLDS OF HALO ORBITS

Now, a patched conic approximation for the interplanetary transfer is assumed linking the Earth and Mars manifolds associated with Halo orbits in the Hill three-body model around the Earth and Mars and in the real Ephemeris model between Earth sphere and Mars sphere. We focus our attention on a transfer between Earth and Mars. However, these results can be applied to other planets of the solar system as well. We investigate a solution to connect the Earth and Mars Halo manifolds with interplanetary trajectories by varying the departure and arrival dates from/to Earth and Mars, and by varying the size of the Earth and Mars Halo orbits, assuming impulsive maneuvers near the surface of planets. Here, the required cost for varying the size of Halo orbits is small compared to the cost for the interplanetary transfer (about 40 m/s with nearly 120 days [33]).

Tables 1 and 2 show the $\Delta V$ and TOF for the transfer from Earth L1 Halo orbit to Mars L2 Halo orbits, using the Ephemeris data for a time interval between 2009 and 2015. “$\Delta V_{\text{E_Phasing_Transfer}}$” and “$\Delta V_{\text{M_Phasing_Transfer}}$” represent above-mentioned maneuvers to adjust the size of Earth and Mars Halo orbits for the Earth-Mars interplanetary transfer, respectively (Maneuver No. 4 and 9; See Table 3). “$\Delta V_{\text{E_Halo_Depart}}$” and “$\Delta V_{\text{M_Halo_Insert}}$” indicate impulsive maneuvers to reduce the between periapsis of manifolds and points on Halo orbit (No. 5 and 8). In general, the time of flight (TOF) is long for the escape and capture on the Halo orbit using the unstable and stable manifolds because the manifolds orbit around the L1/L2 point several times. By applying only the little impulsive maneuvers at the periapsis of the
manifold and at the point on the Halo orbit, the TOF could decrease considerably [32]. “ΔV_E_Escape” is performed at perigee of the unstable manifold of the Earth L1 Halo orbit for the interplanetary transfer (No. 6). “ΔV_M_Capture” is used at periapsis of the stable manifold for the capture to Mars L2 Halo orbit (No. 7). “A_y_E” and “A_y_M” indicate y-amplitudes of the Earth and Mars Halo orbits, meaning optimal Earth and Mars Halo size for ΔV. As a result, interplanetary trajectories between Earth Halo orbits and Mars Halo orbits with reasonable total ΔV and TOF were found. The almost same goes for a return transfer from Mars L2 Halo orbit to Earth L1 Halo orbit.

5. Application to Earth-Mars Transportation System

5.1. Application to Earth-Mars Transportation System using Spaceports at Halo Orbits

In this section, an application to Earth-Mars transportation system, between Low Earth Orbits (LEO) and Low Mars Orbits (LMO), using spaceports at Earth and Mars Halo orbit is discussed and compared with a direct transfer system.

Tables 3 and 4 show the required ΔV and TOF for a transfer from LEO (altitude = 300 km) to LMO (altitude = 200 km) via the Earth and Mars Halo orbits and for a direct transfer case using ephemeris data from 2009 to 2013. “ΔV_LEO” and “ΔV_LMO” are maneuvers for a transfer from LEO to Earth Halo orbit and from Mars Halo orbit to LMO, respectively (Maneuver No. 1 and 12). “ΔV_E_Halo_Insert” and “ΔV_M_Halo_Insert” are performed to reduce TOF between LEO/LMO and Earth/Mars Halo orbit (No. 2 and 11), and “ΔV_E_Phasing_LEO” and “ΔV_M_Phasing_LMO” indicate phasing maneuvers to adjust the size of the Earth and Mars Halo orbits for transfers between LEO/LMO and Earth/Mars Halo orbits (No. 3 and 10). It was found that the required total ΔV for a transfer from LEO to LMO via Earth and Mars Halo orbits is slightly greater than that of the direct transfer, and the TOF is longer. The almost same thing could be said for return transfers from the LMO to LEO via Mars and Earth Halo orbits. Considering the round-trip transfer between LEO and LMO, phasing maneuvers to adjust the size of Earth and Mars Halo orbits for return interplanetary transfers (“ΔV_E_Phasing_transfer” and “ΔV_M_Phasing_transfer”) are as small as mentioned before [33]. On the other hand, phasing maneuver to adjust the phase of LMO for return interplanetary transfers could be large. From these results, the system using Halo orbits has no advantage over the direct transfer with respect to ΔV and TOF. However, the system using Halo orbits is evaluated from a different standpoint in the next section.

<table>
<thead>
<tr>
<th>Departure &amp; Arrival date</th>
<th>ΔV_E Phasing Transfer</th>
<th>ΔV_E Halo Depart</th>
<th>ΔV_E Escape</th>
<th>ΔV_M Capture</th>
<th>ΔV_M Halo Insert</th>
<th>ΔV_M Phasing Transfer</th>
<th>Total ΔV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep. 2009 ~ Oct. 2010</td>
<td>0.04</td>
<td>0.09</td>
<td>0.88</td>
<td>0.93</td>
<td>0.04</td>
<td>0.04</td>
<td>2.02</td>
</tr>
<tr>
<td>Oct. 2011 ~ Oct. 2012</td>
<td>0.04</td>
<td>0.06</td>
<td>0.69</td>
<td>1.01</td>
<td>0.04</td>
<td>0.04</td>
<td>1.88</td>
</tr>
<tr>
<td>Nov. 2013 ~ Oct. 2014</td>
<td>0.04</td>
<td>0.06</td>
<td>0.56</td>
<td>1.10</td>
<td>0.04</td>
<td>0.04</td>
<td>1.84</td>
</tr>
</tbody>
</table>

(ΔV = km/s)

<table>
<thead>
<tr>
<th>Departure &amp; Arrival date</th>
<th>TOF Phasing Transfer</th>
<th>TOF E.Halo ~ E.Peri</th>
<th>TOF E.Peri ~ M.Peri</th>
<th>TOF M.Peri ~ M.Halo</th>
<th>TOF Phasing Transfer</th>
<th>Total TOF</th>
<th>A_y_E</th>
<th>A_y_M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep. 2009 ~ Oct. 2010</td>
<td>120</td>
<td>62</td>
<td>384</td>
<td>117</td>
<td>120</td>
<td>803</td>
<td>0.743</td>
<td>0.571</td>
</tr>
<tr>
<td>Oct. 2011 ~ Oct. 2012</td>
<td>120</td>
<td>69</td>
<td>356</td>
<td>117</td>
<td>120</td>
<td>782</td>
<td>0.729</td>
<td>0.558</td>
</tr>
<tr>
<td>Nov. 2013 ~ Oct. 2014</td>
<td>120</td>
<td>69</td>
<td>318</td>
<td>117</td>
<td>120</td>
<td>744</td>
<td>0.739</td>
<td>0.547</td>
</tr>
</tbody>
</table>

(TOF = days, A_y = million km)
Table 3 Required $\Delta V$ for the transfer from LEO to LMO

<table>
<thead>
<tr>
<th>Transfer type (Departure date from LEO)</th>
<th>$\Delta V_{\text{LEO}}$</th>
<th>$\Delta V_{\text{E.Halo Insert}}$</th>
<th>$\Delta V_{\text{E.Halo Phasing LEO}}$</th>
<th>$\Delta V_{\text{E.Halo Phasing Transfer}}$</th>
<th>$\Delta V_{\text{E.Halo Depart}}$</th>
<th>$\Delta V_{\text{M.Halo Insert}}$</th>
<th>$\Delta V_{\text{M.Halo Phasing Transfer}}$</th>
<th>$\Delta V_{\text{M.Halo Depart}}$</th>
<th>$\Delta V_{\text{LMO}}$</th>
<th>Total $\Delta V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Via Halo (in 2009)</td>
<td>3.15</td>
<td>0.06</td>
<td>0.04</td>
<td>0.09</td>
<td>0.88</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>1.42</td>
</tr>
<tr>
<td>Direct (in 2009)</td>
<td></td>
<td></td>
<td>(0–5.0)</td>
<td>3.67</td>
<td>2.03</td>
<td>(0–2.0)</td>
<td>(0–2.0)</td>
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<td>(0–2.0)</td>
<td>5.70</td>
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<tr>
<td>Via Halo (in 2011)</td>
<td>3.15</td>
<td>0.06</td>
<td>0.04</td>
<td>0.06</td>
<td>0.69</td>
<td>1.01</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>1.42</td>
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<td>Direct (in 2011)</td>
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<td></td>
<td>(0–5.0)</td>
<td>3.63</td>
<td>2.16</td>
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<td>5.79</td>
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<td>Via Halo (in 2013)</td>
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<td>0.56</td>
<td>1.10</td>
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<td>0.04</td>
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<td>Direct (in 2013)</td>
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<td></td>
<td>(0–5.0)</td>
<td>3.64</td>
<td>2.39</td>
<td>(0–2.0)</td>
<td>(0–2.0)</td>
<td>(0–2.0)</td>
<td>(0–2.0)</td>
<td>5.03</td>
</tr>
</tbody>
</table>

($\Delta V = \text{km/s}$)

Table 4 Required TOF for the transfer from LEO to LMO

<table>
<thead>
<tr>
<th>Transfer type (Departure date from LEO)</th>
<th>TOF</th>
<th>E.Halo</th>
<th>E.Phasing LEO</th>
<th>TOF</th>
<th>E.Phasing LEO</th>
<th>TOF</th>
<th>E.Phasing LEO</th>
<th>TOF</th>
<th>M.Halo</th>
<th>M.Phasing LEO</th>
<th>TOF</th>
<th>M.Halo</th>
<th>M.Phasing LEO</th>
<th>TOF</th>
<th>M.Halo</th>
<th>M.Phasing LEO</th>
<th>Total TOF</th>
</tr>
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<tbody>
<tr>
<td>Via Halo (in 2009)</td>
<td>69</td>
<td>120</td>
<td>120</td>
<td>62</td>
<td>384</td>
<td>117</td>
<td>120</td>
<td>120</td>
<td>117</td>
<td></td>
<td>1226</td>
<td></td>
<td></td>
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<tr>
<td>Via Halo (in 2011)</td>
<td>69</td>
<td>120</td>
<td>120</td>
<td>69</td>
<td>356</td>
<td>117</td>
<td>120</td>
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<td></td>
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<tr>
<td>Direct (in 2011)</td>
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<tr>
<td>Via Halo (in 2013)</td>
<td>69</td>
<td>120</td>
<td>120</td>
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<td>Direct (in 2013)</td>
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</table>

($\text{TOF} = \text{days}$)

5.2 Evaluation of the Earth-Mars Transportation System using Halo Orbits

The Earth-Mars transportation system using spaceports at Earth and Mars Halo orbits is evaluated by the spacecraft mass for the round-trip transfer. Here, we assume the following things:

- Payload mass carried during round-trip transfer is normalized to one.
- The specific impulse (Isp) of spacecraft is 300 seconds.
- Structure and bus mass is 4 times heavier than the payload mass.
- The propellant for return from Earth Halo orbits to LEO is left at spaceport on Earth Halo orbits on the way to LMO.
- The propellant for return from Mars Halo orbits to Earth Halo orbits is left at spaceport on Mars Halo orbits on the way to LMO.

From Table 5, compared with direct transfer between LEO and LMO, it is shown that the mass of the Earth-Mars transportation system S/C is reduced by half when starting from LEO using spaceports on Earth and Mars Halo orbits to leave propellant for the return transfer. The reason is simply because it is not necessary to carry the whole propellant for the return to LMO. First, the propellant for returning from Earth Halo orbits to LEO (the value is 10.1 [unitless]) is left at the spaceport on Earth Halo orbits. And then, the propellant necessary for returning from the Mars Halo orbit to the Earth Halo orbit (6.1) is left at the spaceport on Mars Halo orbits. Consequently, the propellant for the transfer from LMO to Mars Halo
orbit (3.3) should be only carried to LMO. Therefore, it can be concluded that this round-trip transportation system using
spaceport at the Earth and Mars Halo orbits is effective by leaving fuel. For comparison, Fig. 5 shows the wet mass (the dry
mass and the required propellant mass) starting from LEO in the case of nonleaving propellant at neither of spaceports, the
case of leaving propellant at only the Earth spaceport, the case of leaving propellant at both Earth and Mars spaceports,
and the case of direct transfer. Numbers in figure (1 ~ 24 and i ~ iv) correspond to the maneuver number in Tables 3 and
for return transfer from Mars to Earth. We can say that the leaving propellant at both the Earth and Mars spaceports is the best
strategy.

### Table 5 Required mass for the round-trip transfer between LEO and LMO

<table>
<thead>
<tr>
<th>Type</th>
<th>Via Earth and Mars Halo orbits to leave propellant for return transfer</th>
<th>Direct</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LEO ~ E.Halo</td>
<td>E.Halo ~ M.Halo</td>
</tr>
<tr>
<td>ΔV [km/s]</td>
<td>3.25</td>
<td>1.84</td>
</tr>
<tr>
<td>Propellant ratio</td>
<td>0.669</td>
<td>0.465</td>
</tr>
<tr>
<td>Payload mass</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Structure &amp; bus mass</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Carried propellant mass</td>
<td>42.3</td>
<td>14.9</td>
</tr>
<tr>
<td>Consumed propellant mass</td>
<td>95.6 (a)</td>
<td>17.3 (b)</td>
</tr>
<tr>
<td>Wet mass</td>
<td><strong>142.9</strong></td>
<td>37.2</td>
</tr>
</tbody>
</table>

**Fig. 5: Dry mass and propellant mass.**
CONCLUSIONS
This paper discussed the links between interplanetary trajectory and escape/capture trajectories from/to Halo orbits. The survey found interplanetary trajectories between Earth L1 Halo orbit and Mars L2 Halo orbits with reasonable delta-V and flight time.
Next, our strategy is applied to the Earth-Mars transportation system. The required delta-V for the round-trip transfer between LEO and LMO via spaceports on Earth and Mars Halo orbits becomes slightly larger than that of the direct round-trip transfer. However, in an evaluation in terms of the required spacecraft wet mass of the Earth-Mars transportation system putting spaceports at Halo orbits, the wet mass starting from LEO could be reduced by half compared to the direct transfer by leaving propellant for return at spaceports at the Earth and Mars Halo orbits on the way to LMO.

REFERENCES