Off-Nominal Trajectory Design of NRHO Transfer for Crewed Mission to Gateway

Junji Kikuchi(1), Yuki Matsumoto(2), Satoshi Ueda(1)

(1) Japan Aerospace Exploration Agency (JAXA)
Sagamihara, Japan
Email: kikuchi.junji@jaxa.jp

(2) Japan Aerospace Exploration Agency (JAXA)
Tsukuba, Japan

The construction of Gateway in lunar orbit is planned as a post-ISS mission. This paper proposes a recovery trajectory for Gateway transfer of crewed missions. Recovery trajectories in the event of a failed maneuver are essential to mission design. The In-Direct transfer, a nominal trajectory candidate, is scheduled for two maneuvers. Assuming the case where these maneuvers fail, the required TCM timing and required fuel consumption are presented.

I. INTRODUCTION

NASA and other space agencies are planning Gateway, a new manned station in lunar orbit [1]. One of the candidates under consideration for the Gateway orbit is the Near-Rectilinear Halo Orbit (NRHO) [2].

The In-Direct Transfer (IDT) is a candidate for the transfer trajectory for the crewed mission [3,4]. IDT is a Moon flyby that performs a Powered Lunar Swing-By (PLSB) at the perilune. The spacecraft approaches NRHO after a day and transitions by an NRHO Insertion (NRHOI). This method has a short transition period of less than one week, making it ideal for manned missions. However, a large ΔV is required to change the orbit, reducing the cargo that can be carried.

A recovery trajectory design of an In-Direct is essential for crewed missions, but the NRHO transition has not been studied. It is difficult to recover from a maneuver failure during PLSB and NRHOI because of the transition to deep space. Matsumoto et al. proposed an off-nominal plan for maneuver failure [5]. Their plan shows a return to NRHO with a small ΔV, but it takes 180 days for a PLSB failure and over 70 transition days for an NRHOI failure. In addition, the difficulty of designing trajectories in all epochs is discussed. Because transitions of more than 70 days are not possible in for a crewed mission, other recovery trajectories must be found.

This paper proposes a recovery trajectory in NRHO transfer for a crewed mission. If the PLSB fails, returning to NRHO in an acceptable number of days is difficult. Thus, we considered a return to Earth. A few days after a PLSB failure, it is possible to return to the Moon two weeks later by decelerating. Then, the spacecraft can return to Earth using another PLSB. With this approach, the spacecraft can return to Earth one month after the failure.

Next, the paper considers the case of a successful PLSB and a failed NRHOI. Returning to Earth with the remaining propellant is difficult since the spacecraft has already decelerated in the PLSB. Thus, the Perilune Rendezvous Method (PRM) is used to return to NRHO. PRM is a transfer trajectory to NRHO discovered by Kikuchi et al. in 2022.[2] This method injects the spacecraft into NRHO with a small ΔV by orbiting the Moon in multiple elliptical orbits. Six days after an NRHOI failure, several TCMs are performed, and injection into a lunar elliptical orbit of the PRM is done. The spacecraft can transition to NRHO with a small fuel consumption within one month.

Our study designed a nominal transfer trajectory to NRHO by IDT. This paper presents the proposed designs for PLSB and NRHOI failure. Using this method, the astronauts can return to Earth or NRHO in approximately one month. In summary, these recovery trajectories will contribute to the design of future crewed missions.

II. NEAR-RECTILINEAR HALO ORBIT (NRHO)

The NRHO is a member of the Halo orbital group, having a long elliptical orbit with an apogee of 70,000 km, and a perigee of 3,000 km as shown in Fig 1. NRHO has a 9:2 monthly resonance, averaging nine revolutions every two months [6]. This orbit is a suitable Gateway with several advantages, such as a small ΔV and long visibility from the Earth [7,8]. For the orbital elements of the Gateway orbiting the NRHO, refer to the reference [9].

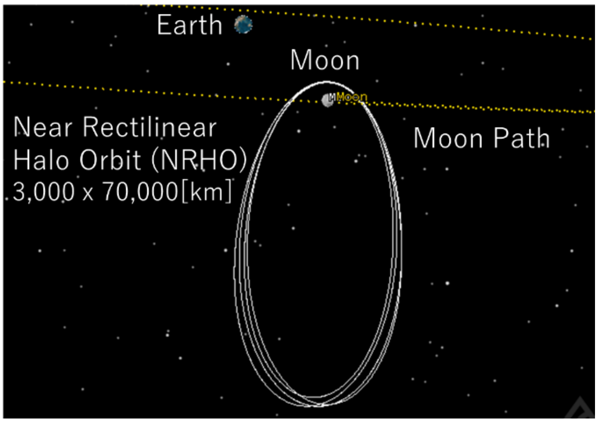

Fig. 1. Near Rectilinear Halo Orbit (NRHO)

III. NOMINAL TRAJECTORY DESIGN

This analysis assumes that a rocket injected the spacecraft into a Lunar Transfer Orbit (LTO). A few days later, the spacecraft reached the vicinity of the Moon. In the IDT, the spacecraft operates PLSB at the perilune. Then, the spacecraft can be injected into NRHO by NRHOI after one day.

The nominal trajectory of the IDT as shown in Fig 2, was designed by back propagation from NRHO. The analysis used the STK Astrogator, a general-purpose orbit and mission analysis tool that can output orbit propagation results after a given time under the gravitational effect of multiple celestial bodies after an initial orbital state and maneuver are input. It considers the gravity of the Earth, the Moon, and the Sun. Solar radiation pressure and air resistance are not considered in order to avoid fluctuations in the trajectory design, which depends on the spacecraft's surface area. The maneuver is analyzed as an impulse. Table 1 summarizes the ephemeris, gravitational field, and the Sphere of Influence (SOI).

A grid search analysis was performed with the conditions shown in Table 2 to design the nominal trajectory Past studies have shown that it is more efficient when NRHOI of the IDT is performed at a true anomaly τ of 160 degree [10]. Therefore, the initial solution is analyzed as $\tau = 160degree$. NRHOI targets the perilune altitude and is adjusted according to the τ and ΔV. PLSB targets the orbit inclination i_{Earth} and perigee altitude h_{Earth} and is adjusted per the ΔV. A solution that satisfies the constraints can be found from the iterative Newton-Raphson method.

Fig 3 shows a color map showing total ΔV with Moon altitude at PLSB and True Anomaly τ as variables. A lower PLSB altitude reduces the ΔV to maximize the effect of lunar swing-by. However, operating a lunar swing-by below 100 km has a high risk of impact with the Moon due to various disturbances. Therefore, in this analysis, the nominal trajectory is adopted with the lower limit of altitude at PLSB set to 100 km and τ of 160 degree. Table 3 shows the ΔV and the interval of the nominal trajectory from rocket's launch. The spacecraft can reach NRHO as short as 6.6 days by IDT. On the other hand, the ΔV of NRHOI is inefficient because it contains large non-velocity vector increments. This has the disadvantage that the spacecraft consumes more fuel and reduces the payload volume.

The following section discusses the recovery trajectory when off-nominals occur during PLSB and NRHOI.

Table 1. Analysis conditions of parameters

Property	Analysis Condition
Gravity model	Earth : EGM2008 21degree Moon : LP150Q 48degree Sun : Point Mass
SOI	Earth : 927,000km Moon : 66,000km
Ephemeris	DE430

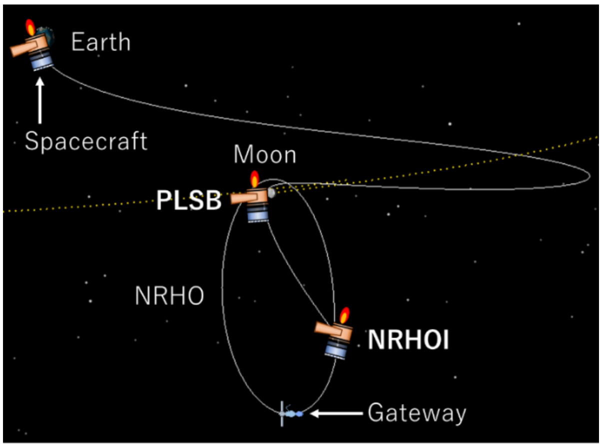

Fig. 2. Trajectory of In-Direct Transfer (IDT)

Table 2. Analysis conditions of optimization of IDT

Property	NRHOI	PLSB
Control Variables	$\Delta V_{NRHOI}, \tau$	ΔV_{PLSB}
Constraint Condition	h_{PLSB}	$i_{Earth} = 30[deg]$
	-	$h_{Earth} = 300[km]$

Table 3. ΔV and transfer period of IDT

Parameter	ΔV[m/s]	Interval Period[day]
Launch	-	0.0
PLSB	173.3	5.4
NRHOI	216.9	1.2
Total	**390.2**	**6.6**

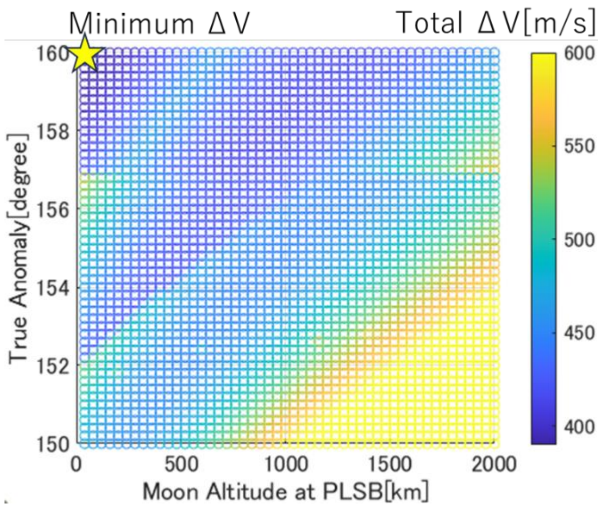

Fig. 3. Relationship between h_{PLSB}, τ and ΔV

IV. PLSB Recovery Trajectory

The discussion in this section assumes the spacecraft that transfers the nominal trajectory of the IDT designed in Section III. The recovery trajectory is designed for the spacecraft in the case of an off-nominal event during PLSB.

A. *Thrust Failure Case (PLSB = 50~100%)*

This section assumes that the PLSB was operated, but ΔV was short of the planned value. In this case, the spacecraft cannot reach the target injection point of NRHO. Therefore, a Trajectory Correction Maneuver (TCM) is required to compensate for the insufficient ΔV. The duration from PLSB to NRHOI is approximately one day. A TCM can be performed within this period to reach the nominal NRHOI position.

First, the mounted fuel for off-nominal use depends on each mission. Furthermore, the amount of PLSB and the interval period until TCM can be performed after PLSB also depends on the off-nominal situation. Therefore, this analysis will utilize a general database of off-nominal occurrence cases in PLSB. The amount of insufficient PLSB and the TCM operation interval are set as variables. The total ΔV including TCM is determined as a result. If the amount of PLSB does not reach 50%, it is considered difficult to continue the TCM, so it is excluded from the scope of this analysis. The target of TCM is the position of NRHOI. A solution that satisfies the constraints can be found, as shown in Table 4.

Fig 4 shows the case where the PLSB performance was 70% and TCM was operated 6 hours after PLSB. The insufficient PLSB made it difficult to reach the nominal NRHOI position. However, TCM allows spacecraft to return to the nominal path. Table 5 summarizes the ΔV for the transfer period. In this case, 200 m/s is required as the additional ΔV.

Fig 5 is a color map showing total ΔV with an insufficient ratio of PLSB and interval period to TCM as variables. The required TCM increases with the amount of insufficient PLSB. Furthermore, the longer the interval period to the TCM, the more the amount increases. This is because the spacecraft's trajectory deviates from the nominal path due to the shortage of PLSB. As a result, large changes in the velocity direction to NRHO will be required.

From these results, it is possible to reach the nominal NRHOI position even if the amount of PLSB is insufficient, depending on the amount of TCM for off-nominal use and the interval period of TCM. On the other hand, if the PLSB can hardly be operated, this method cannot be uses for the recovery trajectory to NRHO. A solution to this case is described in the following section.

Table 4. Analysis conditions of optimization in case of thrust failure (PLSB = 50~100%)

Property	TCM	NRHOI
Control Variables	ΔV_{TCM}	ΔV_{NRHOI}
Constraint Condition	Position of NRHOI	Velocity of NRHO

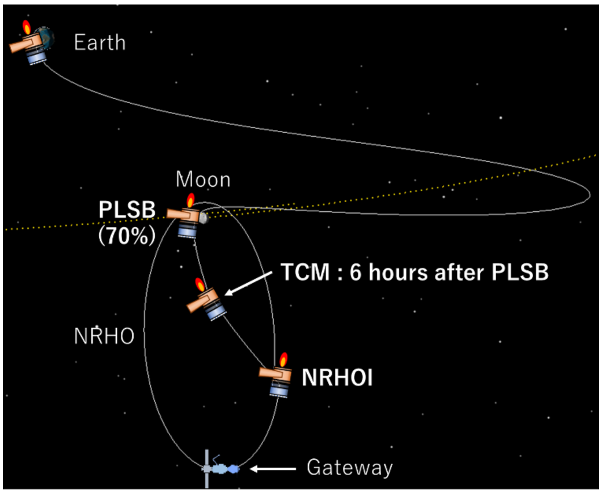

Fig. 4. Example of Recovery Trajectory in case of 70% PLSB and TCM after 6 hours

Table 5. ΔV and transfer period in case of 70% PLSB and TCM after 6 hours

Parameter	ΔV[m/s]	Interval Period[day]
Launch	-	0.0
PLSB (70%)	121.3	5.4
TCM	225.2	0.3
NRHOI	243.7	0.9
Total	**590.2**	**6.6**

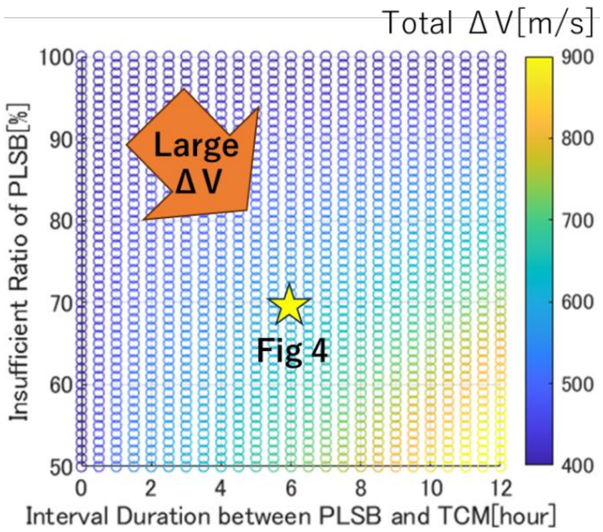

Fig. 5. Relationship between Insufficient PLSB, Interval Duration of TCM, and ⊿V

B. *Thrust Failure Case (PLSB = 0%)*

This section assumes that the spacecraft fails the PLSB and does a lunar flyby. Fig 6 shows an example of orbit propagation without PLSB. The velocity direction of the spacecraft is greatly bent by lunar gravity after a lunar flyby. As a result, the spacecraft will transfer in the direction of a vertical vector relative to the lunar orbital plane and will not be able to rendezvous with the Gateway. This is a critical condition for crewed mission. The proposed method by Matsumoto et al. assumed that the spacecraft would approach the Moon with a small amount of ΔV by waiting for a long orbital period of more than 170 days. However, the transition period is unrealistic for a crewed mission and requires a shorter time.

Thus, this analysis considers giving up the rendezvous with Gateway and returning to Earth. However, the spacecraft will leave the Moon and Earth after the lunar flyby. A change in the direction of the trajectory by a large ΔV would be required to return to Earth. Therefore, it was considered that the spacecraft would approach the Moon again in a short time by decelerating ΔV at the appropriate time after the lunar flyby. Furthermore, the spacecraft will perform TCM after reaching the apolune to transition to a lunar altitude suitable for a lunar gravity swing-by. Then, a method was studied to return to Earth with a small amount of ΔV by accelerating ΔV during the lunar gravity swing-by.

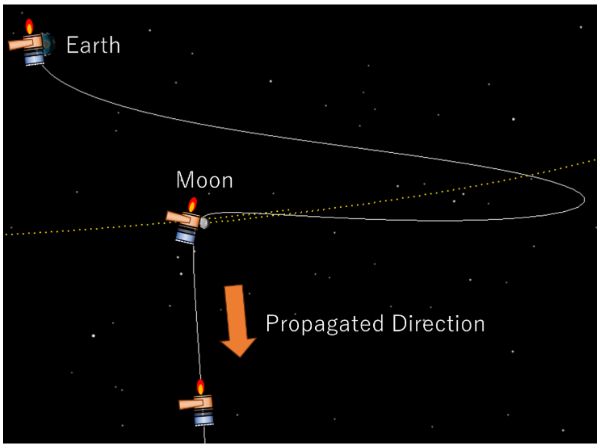

Fig. 6. *Propagated trajectory without PLSB*

Table 6. Analysis conditions of optimization in case of thrust failure (PLSB = 0%)

Property	TCM
Random number	Interval period and amount of Deceleration ΔV
Control Variables	ΔV_{TCM} Acceleration ΔV
Constraint Condition	$h_{Earth} = 300[km]$

In this analysis, the interval period until deceleration ΔV, the amount of deceleration ΔV are searched as random numbers. TCM and the amount of acceleration ΔV of the lunar swing-by maneuver are variables. The perigee altitude h_{Earth} is set as the target. A solution that satisfies the constraints, as shown in Table 6, was found.

An example of an Earth return trajectory in the case of a failed PLSB is shown in Fig 7. Table 7 summarizes the ΔV the transfer period. After the first lunar fly-by, the spacecraft decelerates by a ΔV of 390.3 m/s and is injected into a re-approach to the Moon. This method allows approximately 1.5 days for countermeasures in the case of an off-nominal event. After reaching the apolune, TCM will be accurately operated for a lunar gravity swing-by. Finally, the spacecraft can reach a perigee of 300 km after 5.2 days from acceleration ΔV during the lunar gravity swing-by. These results indicate that returning to Earth is possible within one month of the off-nominal occurrence. Although there is need to mount the small amount of additional fuel for off-nominal, the recovery trajectory can be designed with approximately the same amount of ΔV as nominal.

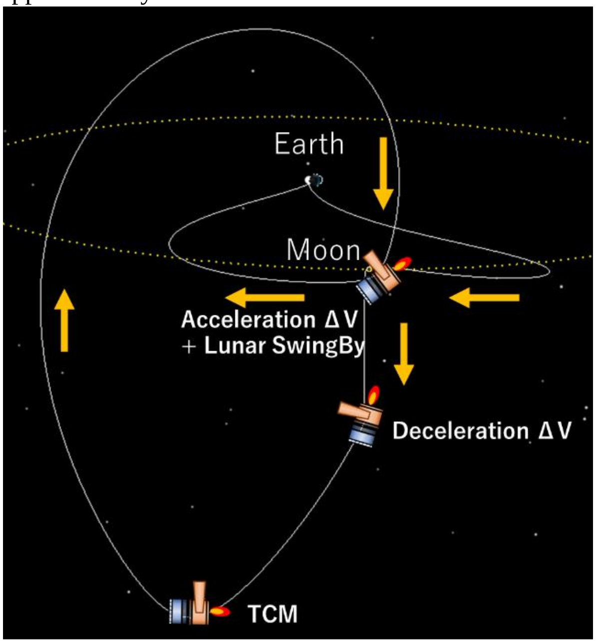

Fig. 7. *Recovery trajectory in case of PLSB failure*

Table 7. ΔV and transfer period of recovery trajectory in case of PLSB failure

Parameter	ΔV[m/s]	Interval Period[day]
Launch	-	0.0
PLSB Failure	-	5.4
Deceleration ΔV	390.3	1.5
TCM	0.5	8.1
Acceleration ΔV	64.8	16.7
Return to Earth	-	5.2
Total	**455.6**	**36.9**

V. NRHOI Recovery Trajectory

This section assumes that the spacecraft transits the nominal trajectory designed in Section III and operates the PLSB as nominal. The recovery trajectory is designed for the spacecraft in the event of an off-nominal during NRHOI.

A. Insufficient Thrust Case (NRHOI = 50~100%)

This section assumes a case where NRHOI was performed, but ΔV was short of the planned value. The trajectory deviates gradually from the NRHO. Therefore, a TCM is required to compensate for the insufficient ΔV. The target position of TCM is the apolune of NRHO. The period from the NRHOI to the apolune of NRHO is about two days, and TCM is performed within this period. The perilune is not evaluated as a target point because of the high orbital velocity and dynamics variability at the perilune.

As with PLSB, the insufficient amount of NRHOI, the allowable fuel consumption for off-nominal, and the interval until TCM can be performed depend on the mission. Therefore, the amount of insufficient NRHOI and the TCM operation interval are set as variables. The total ΔV including TCM is determined. If the amount of NRHOI does not reach 50%, it is difficult for the TCM to continue and is excluded from the scope of this analysis. The target of TCM is the apolune of NRHO. A solution that satisfies the constraints, as shown in Table 8, was found.

Fig 8 shows, for example, a case where the NRHOI performance was 70% and TCM was operated 24 hours after NRHOI. The insufficient NRHOI made it difficult to reach the apolune of NRHO. However, TCM allows spacecraft to return to the nominal path. Table 9 summarizes the ΔV for the transfer period. In this case, 110 m/s is required for the additional ΔV.

Fig 9 is a color map showing the total ΔV with an insufficient ratio of NRHOI and interval period to TCM as variables. The required TCM increases with the amount of insufficient NRHOI. Furthermore, the longer the interval period to the TCM, the more the amount increases. In particular, an increase in the amount of the TCM due to insufficient of NRHOI was significant.

On the other hand, the TCM of Section IV A has a short period as one day between PLSB and NRHOI. However, if the NRHOI could be operated to some extent, it is possible to orbit in the vicinity of NRHO. Therefore, it is not necessary to target the first apolune of NRHO. If the first apolune of NRHO is targeted, the TCM amount increases with a longer TCM interval. Thus, it is evaluated whether it is possible to return to NRHO by targeting the apolune after one revolution.

Table 8. Analysis conditions of optimization in case of thrust failure (NRHOI = 50~100%)

Property	TCM	NRHOI2
Control Variables	ΔV_{TCM}	ΔV_{NRHOI2}
Constraint Condition	Position of NRHO Apolune	Velocity of NRHO Apolune

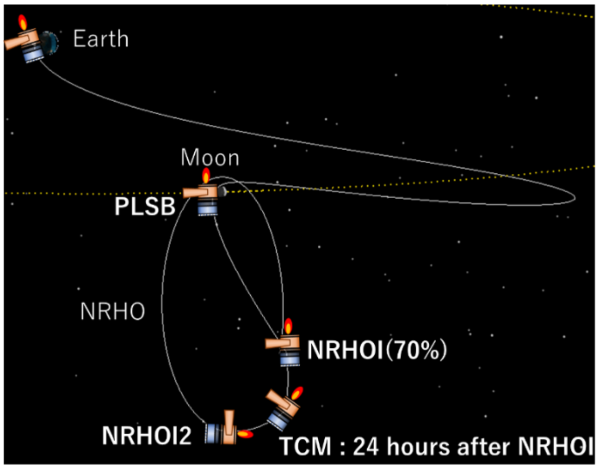

Fig. 8. Example of Recovery Trajectory in case of 70% NRHOI and TCM after 24 hours

Table 9. ΔV and transfer period in case of 70% NRHOI and TCM after 24 hours

Parameter	ΔV[m/s]	Interval Period[day]
Launch	-	0.0
PLSB	173.3	5.4
NRHOI (70%)	151.9	1.2
TCM	118.5	1.0
NRHOI2	59.6	1.1
Total	**503.3**	**8.7**

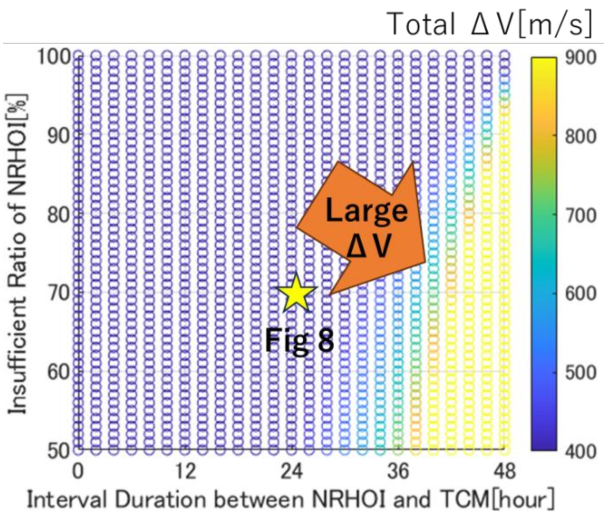

Fig. 9. Relationship between Insufficient NRHOI, Interval Duration of TCM, and ⊿V

Variables are the same as in Table 8. However, the target for TCM is the apolune of the NRHO after one revolution. Furthermore, the TCM interval period for analysis is up to 5.5 days (132 hours) after NRHOI.

Fig 10 shows, for example, a case where the NRHOI performance was 70%, and TCM was operated five days (120 hours) after NRHOI. The insufficient NRHOI gradually leads the spacecraft to deviate from NRHO. However, a TCM allows it to return to the apolune after one revolution. Table 10 summarizes the ΔV the transfer period. In this case, 110 m/s is required as the additional ΔV.

Fig 11 shows a color map showing total ΔV with an insufficient ratio of NRHOI and interval period to TCM as variables. The required TCM increases with the amount of insufficient NRHOI. Furthermore, the longer the time until the TCM, the more the amount increases. Unlike the results in Fig 9, the spacecraft can be reached apolune of the NRHO with a small ΔV for up to 5.5 days.

As a result, targeting the second apolune greatly extends the allowable interval period to TCM. This allows us to plan the recovery trajectory with plenty of time. On the other hand, a small NRHOI may not even return to the apolune. The solutions for cases where this method fails to reach NRHO are presented in the next section.

Table 10. ΔV and transfer period in case of 70% NRHOI and TCM after 24 hours

Parameter	ΔV[m/s]	Interval Period[day]
Launch	-	0.0
PLSB	173.3	5.4
NRHOI (70%)	151.9	1.2
TCM	60.3	5.0
NRHOI2	112.9	6.6
Total	**498.4**	**18.2**

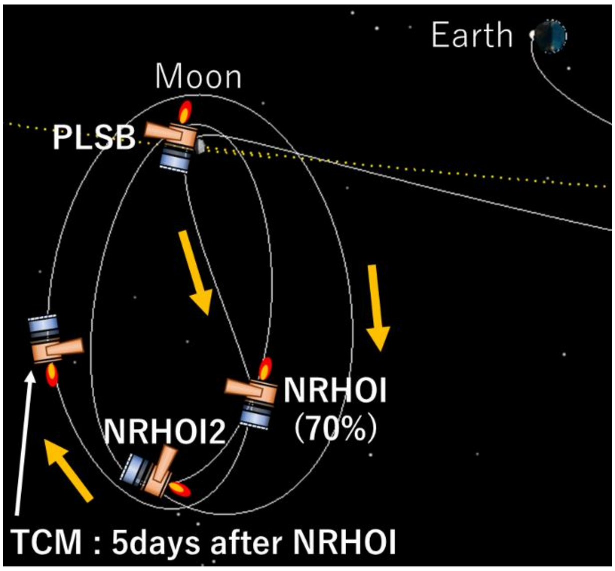

Fig. 10. Example of Recovery Trajectory in case of 70% NRHOI and TCM after 120 hours

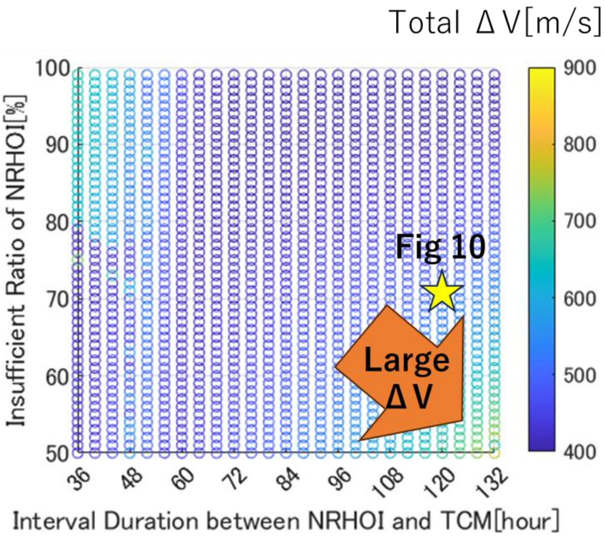

Fig. 11. Relationship between Insufficient NRHOI, Interval Duration of TCM, and ΔV

B. Thrust Failure Case (NRHOI = 0%)

This section assumes that the PLSB is operated normally, but the NRHOI fails. The spacecraft transits straight in the velocity direction vector after PLSB, so the spacecraft passes through the NRHOI target position and gradually moves away from the Moon. The proposed method by Matsumoto et al. also has the long orbital period, more than 70 days. Therefore, the different transfer methods with shorter periods are considered in this analysis. Furthermore, since the PLSB is operated, about 200 m/s of ΔV has already been consumed. Therefore, fuel consumption would increase significantly when returning to Earth, as Section IV B shows. Therefore, consider transitioning to Gateway using a different method.

The Perilune Rendezvous Method (PRM), an intermediate transfer trajectory to NRHO discovered by Kikuchi et al., was proposed in 2022 [11]. The method increases the transition period to two or three weeks longer than IDT but reduces the required ΔV by 50 to 100 m/s. This method is suitable as a transfer trajectory for cargo missions to Gateway.

This analysis considers a method to reach NRHO by transitioning from IDT to PRM. PRM is a method of reaching NRHO by utilizing Earth perturbations during lunar orbit. PLSB is operated at the perilune. After the PLSB, the spacecraft can be injected into a long lunar elliptical orbit. Then, the spacecraft waits for three orbits until the orbital plane coincides with NRHO.

During this time, the orbital period with NRHO is adjusted by performing ΔV at each perilune. Finally, a small amount of acceleration ΔV at the perilune can be injected into NRHO. PRM is characterized by high ΔV efficiency because NRHOI and PLSB are velocity increments only to the velocity direction vector. The details of the PRM design method are described in the reference [12].

However, the nominal orbit with a true anomaly of 160 degree planned in Section III will gradually move away from the Moon if the NRHOI fails. As a result, the spacecraft cannot be injected into a lunar elliptical orbit as well as the PRM. On the other hand, if the true anomaly is about 150 degree, staying in the lunar elliptical orbit is possible even if NRHOI is not operated. However, there is a disadvantage that ΔV increases when the true anomaly is about 150 degree. The results of two propagating trajectories after PLSB designed at each true anomaly are shown in Fig 12. This analysis investigates a method to connect to NRHO from a lunar elliptical orbit with a target true anomaly of about 150 deg. A conceptual diagram of the recovery trajectory is shown in Fig 13.

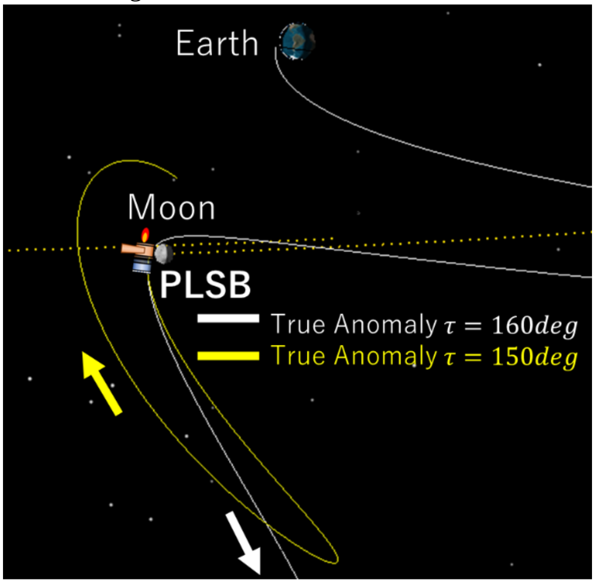

Fig. 12. Propagating trajectories of true anomaly = 160 and 150 degree after PLSB

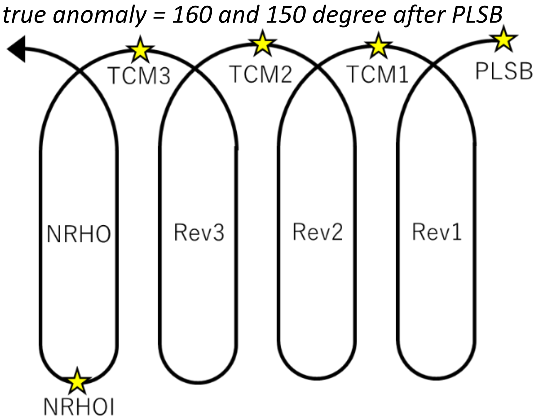

Fig. 13. Conceptual diagram of recovery trajectory

In this analysis, the three ΔV of each perilune are set as the variables, and the apolune of the NRHO is set as the target. Furthermore, the NRHOI is set as the variable, and the apolune velocity of the NRHO is set as the target. A solution that satisfies the constraints as shown in Table 11 was found.

An example of the recovery trajectory for a failed NRHOI is shown in Fig 14. Five days after PLSB, the spacecraft reaches the perilune and operates TCM1. This maneuver maintains the lunar elliptical orbit. After two more TCMs and NRHOI, the spacecraft is injected into the NRHO apolune. Table 12 summarizes the ΔV the transfer period. PRM has higher ΔV efficiency than IDT, so the total ΔV is the same as nominal. This means that no additional fuel is required. On the other hand, the transition period extends for 24 days.

Table 11. Analysis conditions of optimization in case of thrust failure (NRHOI = 0%)

Property	TCM1, 2, 3	NRHOI
Control Variables	$\Delta V_{TCM1}, \Delta V_{TCM2}, \Delta V_{TCM3}$	ΔV_{NRHOI}
Constraint Condition	Position of NRHO Apolune	Velocity of NRHO Apolune

Table 12. ΔV and transfer period of recovery trajectory in case of NRHOI failure

Parameter	ΔV[m/s]	Interval Period[day]
Launch	-	0.0
PLSB	214.1	4.5
NRHOI failure	-	1.0
TCM1	37.4	5.0
TCM2	29.7	7.8
TCM3	9.6	9.7
NRHOI	105.1	2.6
Total	**395.9**	**30.6**

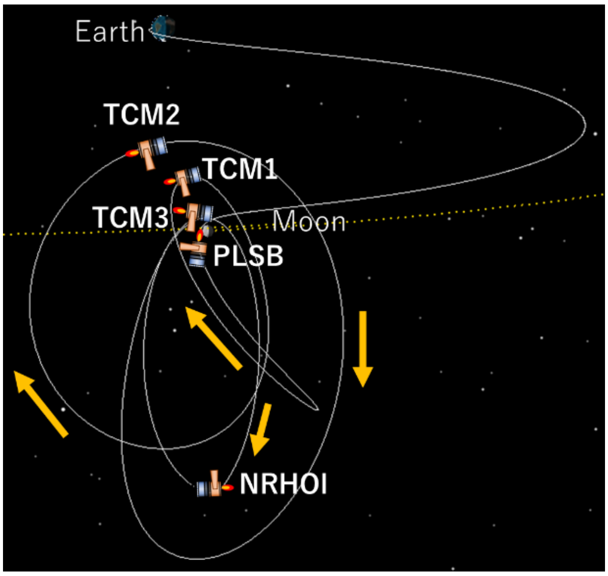

Fig. 14. Recovery trajectory in case of NRHOI failure

VI. CONCLUSION

This paper proposes a recovery trajectory for Gateway transfer of crewed missions. The In-Direct transfer, a nominal trajectory candidate, is scheduled for two maneuvers. First is the PLSB, which is operated at the perilune. The other is NRHOI for injecting the spacecraft into NRHO after one day of PLSB. Recovery trajectories in the event of a failed maneuver are essential to mission design.

If the amount of PLSB was insufficient, the recovery trajectory to reach the nominal NRHOI position by an additional TCM is shown. If the PLSB cannot be operated, a deceleration ΔV can reapproach the spacecraft to the Moon. Subsequently, it was shown that although it would be difficult to inject into NRHO, returning to Earth with a small amount of additional fuel was possible.

If the amount of NRHOI was insufficient, the recovery trajectory to reach the apolune of NRHO by an additional TCM is shown. If NRHOI cannot be operated, ΔV can transition to PRM while keeping the spacecraft in a lunar elliptical orbit. The spacecraft can reach the perilune of NRHO with the nominal fuel consumption.

These ΔV amounts are reasonable, and fuel can be estimated for crewed mission design. The utilization of these transfer methods will make a significant contribution to the scenario design of crewed missions.

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