Orbit Maneuver Compensation of KAGUYA for its Safe and Accurate Lunar Transfer

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Fig. 1. Overview of KAGUYA

Reported in this paper are the results of the orbit maneuver compensation in KAGUYA’s Lunar transfer. Because of the uncoupled allocation of the attitude control thrusters, extra velocity increment (δv) is induced whenever KAGUYA performs an orbit maneuver. Since the observed level of δv was unacceptable range from the point of maneuver accuracy requirement, it was compensated by means of deducting estimated δv from the orbit maneuver command. The δv estimation model was updated step-by-step during the Lunar transfer, which led to significant improvement of the orbit maneuver accuracy and resulted in the omission of the last trajectory correction maneuver. The method of the compensation and its results are introduced in detail.

Key Words: KAGUYA, Orbit Maneuver, Error Compensation

Nomenclature

AOCs : Attitude and orbit control subsystem
HDTV : High definition television
LOI : Lunar orbit injection
O–C : Observation – calculation
RW : Reaction wheel
UTC : Coordinated universal time
VICO : Velocity incremental cutoff
x_HDTV : +x direction in HDTV shot attitude
x_Nom : +x direction in nominal attitude
Δv : Velocity increment
Δv_i : Δv vector
Δv_{i1}, Δv_{i2}, Δv_{i3}, Δv_{i4}, Δv_{i5}, Δv_{i6} : Name of maneuvers (defined in Fig. 3)
δv : Extra velocity increment induced by attitude control
δv_{r} : δv vector
δv_{re} : δv in attitude reorientation
δv_{re,pre} : δv_{re} after orbit maneuver / HDTV shot
δv_{re,post} : δv_{re} before orbit maneuver / HDTV shot
δv_{id} : δv in Idling Mode
δv_{run-down} : δv_{run-down} or δv_{run-up}
δv_{run-up} : δv in Run-up phase of attitude reorientation
δv_{run-up,pre} : δv_{run-up} in Run-up phase of attitude reorientation
δv_{thr} : δv in Thruster Mode
δv_{thr,pre} : δv_{thr} in HDTV shot attitude
δv_{thr,Nom} : δv_{thr} in nominal attitude
δv_{thr,post} : δv_{thr,post} after orbit maneuver
δv_{thr,pre} : δv_{thr,pre} before orbit maneuver
δv_{thr,att} : δv_{thr} in Δv attitude
θ : Rotation angle of attitude reorientation

1. Introduction

KAGUYA (formerly called SELENE, Fig. 1) is a Japanese Lunar explorer, which was launched on September 14, 2007. It was successfully injected into a Lunar orbit on October 3 (dates are expressed in UTC) 1).

Fig. 2 shows the Lunar transfer sequence of KAGUYA 2). KAGUYA was once injected into a long elliptical phasing orbit around the Earth, and after two revolutions on the phasing orbit, it was injected into a translunar trajectory for the final approach to the Moon. At the Lunar encounter, a deceleration maneuver was performed at a perilune passage of the Lunar approaching hyperbolic orbit, and KAGUYA is injected into a Lunar orbit.

In the Lunar transfer phase of KAGUYA (i.e. the period before the Lunar Orbit Injection (LOI)), six orbit maneuvers were planned in all. Their names and roles are listed in Fig. 3. Among those, three maneuvers (Δv_{i1}, Δv_{i4}, and Δv_{i5}) are mandatory ones, which are performed regardless of the actual conditions. On the other hand, the remaining three
maneuvers (a1vΔ, c2vΔ, and c3vΔ) are the adjustment maneuvers, which are performed depending on the results of their previous maneuvers. The execution of the adjustment maneuvers are decided if the required vΔ for these maneuvers exceed their thresholds, which are set at 0.3 m/s, 0.2 m/s and 0.1 m/s respectively. Taking note of c3vΔ (the last correction maneuver), the threshold of 0.1 m/s is set in relation to the perilune altitude of the Lunar approaching hyperbolic orbit. That is to say, as long as the magnitude of the required c3vΔ is smaller than 0.1 m/s, the error of the perilune altitude is limited within the acceptable range (15 km) even though c3vΔ is omitted.

To see this condition as to c3vΔ from the other side, it can be interpreted that the required accuracy for c3vΔ is 0.1 m/s. The reason is that, if the error of c3vΔ is larger than 0.1 m/s, there is a possibility that the error of the perilune altitude exceeds its acceptable range (15 km) depending on the direction of c3vΔ error. Since the direction of c3vΔ error is not controllable, the magnitude of c3vΔ error is required to be less than 0.1 m/s to keep the perilune altitude within the acceptable range regardless of the direction of c3vΔ error.

What should be additionally noted is that, as mentioned before, c3vΔ itself is defined as an adjustment maneuver of its previous maneuvers, and the backup of c3vΔ was not planned in nominal sequence. Therefore, the omission of c3vΔ by achieving the sufficient accuracy in the previous maneuvers is desirable from the point of the risk reduction on the way to the Moon.

These are the backgrounds of the required accuracy for the orbit maneuvers in KAGUYA’s Lunar transfer phase.

In order to achieve this accuracy, the orbit maneuver was compensated to cancel the extra velocity increment induced by the attitude control (δv). δv estimation model was constructed and applied to the orbit maneuver compensation. The objective of this paper is to introduce the method of the orbit maneuver compensation, and to prove the validity of the proposed method based on the actual flight result of KAGUYA.

Table 1. Plan and result of δvΔ, δvαf

<table>
<thead>
<tr>
<th>Item</th>
<th>δvΔ</th>
<th>δvαf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date: Sep. 14, 2007</td>
<td>23.18 m/s</td>
<td>0.58 m/s</td>
</tr>
<tr>
<td>(plan)</td>
<td>23.18 m/s</td>
<td>0.58 m/s</td>
</tr>
<tr>
<td>(actual)</td>
<td>23.57 m/s</td>
<td>0.77 m/s</td>
</tr>
<tr>
<td>(error)</td>
<td>0.39 m/s</td>
<td>0.19 m/s</td>
</tr>
</tbody>
</table>
2. Trigger of Orbit Maneuver Compensation

On the launch date (Sep. 14), the first orbit maneuver $\Delta v_{c1}$ was performed, and it was followed by its adjustment maneuver $\Delta v_{a1}$ on the next day. Their plans and results are summarized in Table 1). $\Delta v$ stands for the velocity increment of the maneuver. “Plan” is the $\Delta v$ derived from the orbit plan prior to the maneuver, “actual” is the $\Delta v$ calculated based on the orbit determination posterior to the maneuver, and “error” is the difference between them. In actual, the maneuver error is composed of the magnitude error and the direction error. However, the magnitude error is mainly discussed from here on, since the orbit maneuver compensation was made only for the magnitude. The reason will be noted later.

The error of $\Delta v_{a1}$ was not so small, but it was not taken so serious. Since $\Delta v_{c1}$ was relatively large maneuver which was performed using the main engine, and its error was planned to be adjusted by succeeding $\Delta v_{a1}$. On the other hand, the error of $\Delta v_{a1}$ was taken as serious. Since $\Delta v_{a1}$ was planned as an adjustment maneuver which was performed using small thrusters, it was expected to be sufficiently accurate. The error of $\Delta v_{a1}$ (0.19m/s) implies that the accuracy requirement of $\Delta v_{a1}$ (0.10m/s) may not be satisfied, since $\Delta v_{a1}$ is supposed to be performed in the same manner as $\Delta v_{c1}$. Therefore, it was noticed that the maneuver error must be reduced in some way.

3. Preliminary Analysis of Maneuver Error

All of the orbit maneuver operation of KAGUYA were planned to be performed when KAGUYA was visible from domestic ground stations. And the range-rate of KAGUYA was continuously monitored during the orbit maneuver operation).

Fig. 4 shows the profile of Observation – Calculation (O–C) of 2-way range-rate around $\Delta v_{a1}$. “Observation” is the 2-way range-rate derived from the actual measurement of the Doppler shift. “Calculation” is the predicted 2-way range-rate data constructed from the latest orbit determination and the orbit maneuver plan. When constructing the predicted data, the orbit maneuver was approximated as an impulsive velocity increment at the mid-point of the maneuver duration. $\Delta v_{a1}$ was performed on 23:00 of Sep. 15, and the duration of the maneuver was about 30 seconds.

Fig 4. shows that the magnitude of O–C gradually increased from the beginning of the profile (1 hour before the maneuver), went through the complex patterns, and came up to 0.33m/s at the end of the profile (1 hour after the maneuver). Considering the direction of the line of sight during the monitoring, this value substantially agrees with the $\Delta v_{a1}$ error calculated from the post-maneuver orbit determination (Note that this is the O–C of “2-way” range-rate).

The first observation to be pointed out is that, except for the large jumps of data around the orbit maneuver, no apparent step of O–C is observed before and after the maneuver. Clearly, the large jumps were induced by the impulsive approximation of the orbit maneuver when constructing “Calculation”, but they can be ignored here. And the absence of apparent step indicates that the orbit maneuver itself achieved sufficient accuracy, which can be estimated as less than 0.01m/s. The attitude and orbit control subsystem (AOCS) of KAGUYA has the function called Velocity Incremental Cutoff (VICO). The data of the accelerometer is monitored and integrated onboard, and the orbit maneuver is automatically cut off at the moment when the target velocity increment is obtained. The observation proves that VICO functioned normally.

From Fig. 4, it is obvious that the error of $\Delta v_{a1}$ was resulted from the acceleration continuously observed in the profile. This acceleration was originated by the translational force induced by the attitude control using the thrusters (Thruster Mode). As shown in Fig. 5, all the thrusters of KAGUYA are mounted on its $-x$ panel, and the thrusters used for the pitch and yaw attitude control are not mounted.
to produce pure control torque in a pair. Therefore, in Thruster Mode, the translational force in +x direction is induced by the attitude control. As a matter of course, this fact has been recognized qualitatively since the KAGUYA’s design phase. However, the extra velocity increment induced by the attitude control (Δv) was not accounted quantitatively in the orbit maneuver plan.

The profile in Fig. 4 suggests that there are several types of the acceleration pattern. By comparing the profile with the operation plan, the correlation between the acceleration patterns and the operations was identified.

First, the large acceleration just after the orbit maneuver (from 23:00 to 23:15) corresponds with “Idling Mode”. Idling Mode is one of the control mode of AOCS, and it is specialized for the stabilization of the attitude motion just after the orbit maneuver. The operation duty of the thrusters in Idling Mode is relatively higher than that in the nominal Thruster Mode to stabilize the attitude under larger disturbance. This results in the larger acceleration observed in the profile. In this case, +x direction, which is the direction of the induced acceleration, always coincides with Δv direction. Therefore, Δv induced in this pattern always acts to increase Δv. The magnitude of Δv induced in this pattern is proportional to a period of time during Idling Mode. Δv induced in this pattern is named Δvidle hereafter.

Secondly, the up-and-down pattern observed around 22:25 and 23:25 corresponds with the attitude reorientation between the nominal attitude and Δv attitude. Δv induced in this pattern cannot be interpreted so simply as the previous one, and it depends on Δv attitude of each orbit maneuver. Δv induced in this pattern is named Δvman hereafter.

Finally, the small gradient observed through the profile corresponds with the nominal Thruster Mode. The acceleration in this mode is much smaller than that in Idling Mode by the reason that already mentioned in the part of Idling Mode. When KAGUYA is in Δv attitude, Δv induced in this pattern always acts to increase Δv. The magnitude of Δv induced in this pattern is proportional to a period of time during Δv attitude. Δv induced in this pattern is named Δvthr hereafter.

These are the preliminary analysis of the maneuver error based on the O–C profile of 2-way range-rate around Δvpl.

4. Maneuver Compensation Process and Results

4.1. Compensation on Δvpl

The first phasing maneuver Δvpl was performed on Sep. 19. Δvpl was relatively large maneuver (about 93m/s) performed by the main engine, and the resulting error was planned to be adjusted by succeeding Δv2. Therefore, the accuracy requirement for Δvpl was not so stringent. A first step of maneuver compensation was applied to this Δvpl.

On the compensation of Δvpl, only the most dominant Δv, that is Δvidle, was considered and it was assumed to be 0.10m/s based on the monitored data of Δvpl.

The plan and result of Δvpl are summarized in Table 2. The item “compensation” means the quantity of Δv compensation to cancel Δv, which is simply the opposite sign of estimated Δv (in this case, -Δvidle = -0.10m/s). The item “command” means the quantity actually set to the orbit maneuver command, and it is simply the total sum of “plan” and “compensation”.

As a result of the compensation, the error of Δvpl got smaller than that of Δvpl. However, the error of Δvpl (0.14m/s) still did not achieve the accuracy requirement of Δvpl (0.10m/s). From this result, it was noticed that further error reduction was necessary.

4.2. Compensation on Δv2

In 19 hours after Δvpl, the adjustment maneuver Δv2 was performed. Following the compensation result of Δvpl, the second step of the maneuver compensation was applied to this Δv2. On Δv2, Δvman was newly considered in Δv estimation, in addition to Δvidle, which was already considered in the previous step.

The magnitude and direction of Δvman depend on the attitude maneuver profile during the orbit maneuver operation. Shown in Fig. 6 is the schematic of the attitude maneuver profile of a typical attitude reorientation. Basically, the attitude maneuver is performed as a rotation...
around a single axis. The rotation angle is expressed as $\theta$ and it is assumed to be 90deg. in Fig. 6. The profile of angular acceleration ($\dot{\theta}$), angular velocity ($\theta$), and $\theta$ are shown in the figure. As is shown in Fig. 6(b), the profile is composed of three phases. They are “Run-up”, “Coasting”, and “Run-down”. As is clear from Fig. 6(a), the attitude control torque is produced only in Run-up and Run-down phase, and the same applied to the translational acceleration induced by the attitude control. And Fig. 6(c) shows that the attitude in Run-up and Run-down phases can be approximated as the initial and terminal attitude of the attitude maneuver. What it comes down to is that $\Delta \nu_{\text{Att}}$ can be modeled as the combination of $\Delta \nu_{\text{Run-up}}$ and $\Delta \nu_{\text{Run-down}}$. $\Delta \nu_{\text{Run-up}}$ stands for $\Delta \nu$ induced in Run-up phase and directs $+x$ direction of the initial attitude. $\Delta \nu_{\text{Run-down}}$ stands for $\Delta \nu$ induced in Run-down phase and directs $+x$ direction of the terminal attitude.

**Fig. 6. Typical profile of attitude maneuver**

Shown in Fig. 7 is the schematic of $\Delta \nu$ estimation in $\Delta \nu_{c2}$, which considers the model of $\Delta \nu_{\text{Att}}$ discussed above. The upper part of the figure shows the schematic of the attitude maneuver profile through the orbit maneuver operation. The lower part of the figure shows the vector diagram of $\Delta \nu$ elements, $\Delta \nu_{\text{Att-pre}}$, $\Delta \nu_{\text{Idle}}$, and $\Delta \nu_{\text{Att-post}}$ were considered in $\Delta \nu$ estimation of $\Delta \nu_{c2}$, where $\Delta \nu_{\text{Att-pre}}$ stands for the $\Delta \nu_{\text{Att}}$ before the orbit maneuver and $\Delta \nu_{\text{Att-post}}$ stands for the $\Delta \nu_{\text{Att}}$ after the orbit maneuver. Additionally, as discussed in the previous paragraph, $\Delta \nu_{\text{Att-pre}}$ and $\Delta \nu_{\text{Att-post}}$ are respectively composed of $\Delta \nu_{\text{Run-up}}$ and $\Delta \nu_{\text{Run-down}}$ which direct $+x$ direction of the attitude in each phase. In the diagram, all $\Delta \nu$ elements are expressed as a vector having its direction. They are connected sequentially, and a vector sum of them gives a $\Delta \nu$ vector ($\Delta \nu$).

Ideally speaking, $\Delta \nu$ vector ($\Delta \nu$) derived from the orbit plan should be compensated in a vector space considering $\Delta \nu$. However, in the actual operation, the procedure to produce a command set from the orbit plan was automated, and the compensation of the maneuver direction required risky procedure modification. Additionally, in most cases, the direction of $\Delta \nu$ is not so far from that of $\Delta \nu$. After all, it was decided that only a component of $\Delta \nu$ in $\Delta \nu$ direction is extracted and is used for the scalar compensation of $\Delta \nu$ derived from the orbit plan.

The $\Delta \nu$ direction component of $\Delta \nu$ in Fig. 7 is obtained by

$$\Delta \nu = (\cos \theta + 1) \Delta \nu_{\text{Run-up}} + \Delta \nu_{\text{Idle}} + (1 + \cos \theta) \Delta \nu_{\text{Run-down}}$$

where $\theta$ denotes the angle between the $+x$ directions of the nominal attitude and $\Delta \nu$ attitude. Additionally, $\Delta \nu_{\text{Run-up}}$ and $\Delta \nu_{\text{Run-down}}$ are assumed to be the same, and are denoted as $\Delta \nu_{\text{Run}}$.

On the compensation of $\Delta \nu_{c2}$, based on the monitored data of $\Delta \nu_{c1}$, the values of $\Delta \nu_{\text{Run}}$ and $\Delta \nu_{\text{Idle}}$ were assumed to be 0.05m/s and 0.10m/s respectively. Additionally, $\theta$ was set to 137.7 deg. which was derived from the orbit plan. Substituting these values to Eq. (1), $\Delta \nu$ was rounded to be 0.12m/s.

The plan and result of $\Delta \nu_{c2}$ are summarized in Table 3. As a result of the compensation, the error of $\Delta \nu_{c2}$ was reduced to 0.02m/s. From this result, it was concluded that the accuracy requirement of $\Delta \nu_{c2}$ (0.10m/s) can be achieved by the compensation based on Eq. (1).

### 4.3. Compensation on $\Delta \nu_{p2}$

The second phasing maneuver $\Delta \nu_{p2}$ was performed on
Sep. 29. In spite of the fact that $\Delta v_2$ is a relatively small maneuver (about 1.7m/s), the resulting error was planned to be adjusted by the succeeding $\Delta v_3$. However, as mentioned before, $\Delta v_3$ was the last maneuver nominally planned before LOI and the backup of $\Delta v_3$ was not planned in nominal sequence. Therefore, if $\Delta v_3$ could have been omitted by achieving the sufficient accuracy in the preceding $\Delta v_2$, it was desirable from the point of the risk reduction on the way to the Moon. From this point of view, based on the compensation result of $\Delta v_2$, the third step of the maneuver compensation was applied to this $\Delta v_2$. On $\Delta v_2$, add to $\delta v_{\text{idle}}$ and $\delta v_{\text{att}}$, which were already considered in the previous step, $\delta v_{\text{thr}}$ was newly considered in $\delta v$ estimation.

$\delta v_{\text{thr}}$ is induced when KAGUYA is in Thruster Mode. It directs $+x$ direction of KAGUYA’s body-fixed frame, and its magnitude is proportional to a period of time during Thruster Mode.

Shown in Fig. 8 is the schematic of $\delta v$ estimation in $\Delta v_2$, accounting $\delta v_{\text{thr}}$. In addition to $\delta v_{\text{att,pre}}$, $\delta v_{\text{idle}}$ and $\delta v_{\text{att,post}}$, which were already considered in the previous step, $\delta v_{\text{thr,pre}}$, $\delta v_{\text{thr,att}}$, and $\delta v_{\text{thr,post}}$ were newly considered as $\delta v$ elements. $\delta v_{\text{thr,pre}}$ and $\delta v_{\text{thr,post}}$ stand for $\delta v_{\text{thr}}$ in the nominal attitude before and after the orbit maneuver. $\delta v_{\text{thr,att}}$ stands for the $\delta v_{\text{thr}}$ in $\Delta v$ attitude. They direct $+x$ direction of the attitude in each phase. A vector sum of all $\delta v$ elements gives $\delta v$. A component of $\delta v$ in $\Delta v$ direction was extracted, and used for the scalar compensation of $\Delta v$ derived from the orbit plan.

The component of $\delta v$ in $\Delta v$ direction in Fig. 8 is obtained by

$$
\delta v = \cos \theta \delta v_{\text{thr,pre}} + (\cos \theta + 1)\delta v_{\text{run}} + \delta v_{\text{thr,att}} + \delta v_{\text{idle}} + (1 + \cos \theta)\delta v_{\text{run}} + \cos \theta \delta v_{\text{thr,post}}
$$

(2)

However, at this stage in the operation, a special operation turned out to be added after $\Delta v_2$. That was the High Definition Television (HDTV) shot of the Earth (Fig. 9). As a result of this change, the attitude maneuver profile of $\Delta v_2$ was modified a little. Instead of maneuvering back to the nominal attitude just after $\Delta v_2$, KAGUYA had stayed in $\Delta v$ attitude for a while until the HDTV operation started.

Shown in Fig. 10 is the schematic of $\delta v$ estimation in $\Delta v_2$, reflecting the modification of the attitude maneuver profile. Since AOCS shifted to Reaction Wheel (RW) Mode shortly after the completion of $\Delta v_2$, the production of $\delta v$ was terminated with $\delta v_{\text{idle}}$. Therefore, $\delta v$ elements $\delta v_{\text{att,post}}$ and $\delta v_{\text{thr,post}}$ are omitted from the vector diagram previously in Fig. 8. A vector sum of all $\delta v$ elements gives $\delta v$. The component of $\delta v$ in $\Delta v$ direction was extracted, and used for the scalar compensation of $\Delta v$ derived from the orbit plan.

The component of $\delta v$ in $\Delta v$ direction in Fig. 10 is obtained by

$$
\delta v = \cos \theta \delta v_{\text{thr,pre}} + (\cos \theta + 1)\delta v_{\text{run}} + \delta v_{\text{thr,att}} + \delta v_{\text{idle}}
$$

(3)

On the compensation of $\Delta v_2$, the values of $\delta v_{\text{run}}$ and $\delta v_{\text{idle}}$ were assumed to be 0.0243m/s and 0.0897m/s respectively, based on the results of $\Delta v_{\text{d1}}$ and $\Delta v_{\text{d2}}$. The result of $\Delta v_{\text{p1}}$ was not used for the estimation of $\delta v_{\text{run}}$ and $\delta v_{\text{idle}}$, since $\Delta v_{\text{p1}}$ was performed by the main engine and $\delta v_{\text{idle}}$ induced in

![Fig. 9. HDTV image of the Earth](image_url)

![Fig. 11. Schematics of $\delta v$ around HDTV shot](image_url)
\( \Delta v_{\text{p1}} \) might differ from that expected in \( \Delta v_{\text{p2}} \). The values of \( \Delta \text{Thr}_{\text{pre}} \) and \( \Delta \text{Thr}_{\Delta\delta\nu} \) were assumed to be 0.015m/s and 0.025m/s respectively based on the monitored data of \( \Delta v_{\text{p1}} \) and the operation plan. Additionally, \( \theta \) was set to 91.2 deg, which is derived from the orbit plan. Substituting these values to Eq. (3), and \( \Delta v \) was estimated as 0.138m/s.

Besides the compensation of \( \Delta v_{\text{p1}} \) itself, the process of planning \( \Delta v_{\text{p2}} \) was also modified to improve its accuracy. \( \Delta v \) expected to be generated during the cruise were estimated and considered in the orbit plan. First, \( \Delta v \) induced during HDTV operation was considered. The schematic of \( \Delta v \) estimation in HDTV operation is shown in Fig. 11. During the operation, KAGUYA’s attitude reorients from \( \Delta v_{\text{p1}} \) attitude through HDTV shot attitude to the nominal attitude. Considered as \( \delta \) elements are \( \Delta \text{Thr}_{\text{pre}} \) before and after HDTV shot \( (\Delta \text{Thr}_{\text{pre}} \, \Delta \text{Thr}_{\text{nom}}) \) and \( \Delta \text{Att} \), the vectors \( x_{\text{HDTV}}, x_{\text{nom}} \) stand for the +x direction of each attitude. A vector sum of all \( \delta \) elements gives \( \Delta v \), which is obtained by

\[
\Delta v = (\Delta \text{Thr}_{\text{pre}} + \Delta \text{Thr}_{\text{nom}}) x_{\text{HDTV}} + (\Delta \text{Thr}_{\text{HDTV}} + 2 \Delta \text{Thr}_{\text{nom}}) x_{\text{HDTV}} + (\Delta \text{Thr}_{\text{nom}} + \Delta \text{Thr}_{\text{nom}}) x_{\text{nom}} \tag{4}
\]

On the estimation of \( \Delta v \) induced in HDTV operation, the value of \( \Delta \text{Thr}_{\text{nom}} \) was assumed to be 0.043m/s based on the value used in \( \Delta v_{\text{p1}} \) compensation, and the values of \( \Delta \text{Thr}_{\text{pre}} \) and \( \Delta \text{Thr}_{\text{nom}} \) were derived from the orbit and the operation plan. Substituting these values to Eq. (4), and \( \Delta v \) induced during HDTV operation was estimated as 0.082m/s. \( \Delta v \) induced by RW unloading was considered in addition. Three operations of RW unloading were planned until LOI. \( \Delta v \) induced by RW unloading was estimated as 0.013m/s based on the preceding operations, and considered in the orbit plan. It must be noted that these \( \Delta v \) were considered in a vector space in the orbit plan (not in a scalar space as in the case of \( \Delta v \) compensation), since the orbit planning software had sufficient flexibility to add new \( \Delta v \) in orbit propagation without serious risk.

The plan and result of \( \Delta v_{\text{p2}} \) are summarized in Table 4. As a result of the compensation, the error of \( \Delta v_{\text{p2}} \) was reduced to 0.008m/s. From this result, it was concluded that \( \Delta v \) accuracy was improved by the compensation based on Eq. (3).

### 4.4. Summary of maneuver compensation process

The results of the maneuver compensation process are summarized in Fig. 11. Evidently, the maneuver accuracy was improved step-by-step as \( \delta \) estimation model was refined. This fact proves the validity of the proposed \( \delta \) estimation model. Additionally, the accuracy improvement from \( \Delta v_{\text{c2}} \) to \( \Delta v_{\text{p2}} \) implies the contribution of the parameters update \( (\delta \text{Thr}_{\text{Run}} \, \delta \text{Thr}_{\text{Idle}}) \) on the results of preceding maneuvers. Finally, it was verified that the accuracy requirement of \( \Delta v_{\text{p2}} \) (0.10m/s) can be achieved by the compensation based on the procedure shown in this section.

### 5. Cancellation of \( \Delta v_{\text{c3}} \)

Based on the orbit determination after \( \Delta v_{\text{p2}} \), the orbit maneuver plan of \( \Delta v_{\text{c3}} \) was drafted. \( \Delta v \) required to achieve the LOI condition was estimated as 0.10m/s, which was just on the threshold to decided its execution. However, the error of the perilune altitude in case of \( \Delta v_{\text{c3}} \) omission was estimated as 4km, which was well within acceptable range. The errors of the other orbit parameters were also within acceptable range, and they were expected to be corrected in the succeeding LOI maneuvers with a small \( \Delta v \) increase. Based on these results, it was decided to cancel \( \Delta v_{\text{c3}} \). As a result, the risks of performing \( \Delta v_{\text{c3}} \) were completely eliminated.

### 6. Conclusion

The orbit maneuver compensation was performed in order to transfer KAGUYA safely and accurately to the Moon. The compensation intended to cancel \( \Delta v \) induced by the attitude control. \( \delta \) estimation model was constructed based on the monitored data of the 2-way range rate during the maneuver in the early phase. The maneuver accuracy was improved step-by-step as the \( \delta \) estimation model was refined. This proves the validity of the proposed \( \delta \) estimation model. Additionally, the parameters update based on the results of the preceding maneuvers is likely to contribute to the accuracy improvement. In conclusion, the appropriate orbit maneuver compensation resulted in the safe and accurate Lunar transfer of KAGUYA.
Reference


6) http://www.jaxa.jp/