SELENE (KAGUYA) ORBIT DETERMINATION RESULTS AND LUNAR GRAVITY FIELD ESTIMATION BY USING 4-WAY DOPPLER MEASUREMENTS

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ABSTRACT

SELENE (Kaguya) is Japan’s first large lunar explorer aims to obtain the scientific data to investigate the origin and the evolution of the moon and to acquire engineering techniques for the future moon exploration and utilization. The nominal mission phase finished at the end of October 2008, and the extended mission phase started from the beginning of November 2008. In order to perform the additional scientific observation, the Kaguya spacecraft had been put into several sets of different orbits compared to the nominal mission phase. At the end of extended mission phase, Kaguya made a controlled impact to the lunar surface on 10 June 2009. The paper describe the results of the orbit determination of Kaguya from the nominal mission phase to the extended mission phase and the lunar impact analysis and its operation results. The present status of lunar gravity field estimation is also described.

1. INTRODUCTION

The Kaguya (SELENE) mission is Japan’s first large lunar exploration mission. The Kaguya spacecraft was launched by the H-IIA rocket on 14 September 2007. After several orbital correction maneuvers and lunar orbit insertion maneuvers, Kaguya was successfully injected into the lunar orbit on 4 October 2007 [1][2]. The Kaguya mission consists of three spacecrafts: the main orbiter Kaguya, the relay sub-satellite Okina, and the VLBI sub-satellite Ouna (Fig.1.). Kaguya was put into 100 km altitude circular orbit, Okina was put into 100×2400 km altitude elliptic orbit, and Ouna was put into 100×800 km altitude elliptic orbit, respectively. The inclination of these spacecrafts are about 90 degrees (with respect to the lunar fixed coordinate system). The objectives of the Kaguya mission are: a) to obtain the engineering and scientific data for the future lunar surface utilization, and b) to obtain the scientific data that make a major contribution to the understanding of the lunar origin and its evolution. In order to perform the scientific observation, the Kaguya spacecraft is equipped with 14 scientific instruments. In addition, High Definition Television (HDTV) are equipped to take pictures of the earth rise and detailed features of the complex crater from slant view, and the image is useful as public information [3].

The paper describes the results of the orbit determination of Kaguya during the nominal observation phase and the extended mission phase. The controlled impact analysis and its operation results are also discussed. In addition, initial results of lunar gravity estimation are described.
2. ORBIT DETERMINATION

The Flight Dynamics Division of the Japan Aerospace Exploration Agency (JAXA) performed the orbit determination and prediction of Kaguya, Okina, and Ouna in order to ensure a steady implementation of the tracking / telemetry and command (TT&C) operation. We provide the orbital information such as the results of the orbit determination, prediction ephemeris, information for tracking stations. These spacecraft’s ephemeris data are also used in the initial scientific analysis.

Fig. 2. shows the overview of the SELENE Flight Dynamics System (SELENE-FDS) and the data distribution flow chart. In the daily operation, the JAXA’s ground station network (GN) and deep space centers were used for the TT&C operation. During the critical phase, we also obtained the tracking data from the Deep Space Network (DSN).

In the SELENE mission, the 2-way S-band range and Doppler measurements are used for the orbit determination of Kaguya, Okina and Ouna. In addition, the 4-way Doppler measurement of
Kaguya via Okina have been obtained in order to improve the gravity model of the moon. This is world’s first to perform the direct observation of the gravity of lunar far-side region. These 4-way Doppler data make considerable contribution to the improvements of the lunar gravity model [4]. Usually, to provide the prediction ephemeris of these spacecrafts for the operation planning and the initial scientific analysis, we perform the orbit determination twice in a week for the Kaguya spacecraft and once a week for the Okina and Ouna spacecrafts, respectively.

In the case of Kaguya, the periodic thrusting events by the angular momentum desaturation (AMD) via mono-propellant 20N and 1N thrusters have an great influence on the orbit determination and prediction accuracy. Because of the configuration of the unified propulsion system (UPS), AMD event generate the small translational acceleration. In order to eliminate the effect of the small $\Delta V$’s caused by AMDs, the tracking data are divide into the each arc spanned by AMD events and perform the orbit determination by using short arc tracking data without the AMD event. Although, we performed the orbit determination without including small $\Delta V$’s, these small $\Delta V$’s are taken into account for the orbit prediction analysis. The magnitude of small $\Delta V$’s are predicted based on actual operation results.

On the other hand, in the case of Okina and Ouna, these spacecrafts adopt the spin stabilized method for the attitude control, so the data arc for the orbit determination are relatively long as compared with Kaguya. In the following subsection, how the orbits evolved around the moon are described.

### 2.1 Nominal Mission Phase

The nominal mission phase lasted about 10 months from the end of initial function check out phase after spacecraft reached its nominal observation orbit in December 2007. During the nominal mission phase, we performed six altitude control maneuvers and three orbital plane control maneuvers to maintain the observation phase orbit (100±30km) and to satisfy the scientific observation requirements.

Fig. 3. shows the evolution of the perilune and apolune altitude of Kaguya. The orbit of Kaguya satisfied the mission requirement. The accuracy of the prediction ephemeris of Kaguya which were used in the actual TT&C operation varies with the geometry of Earth-Moon vector and the Kaguya’s orbital plane. The 2-way range and Doppler measurements have a sensitivity in the line of sight direction, thus when the orbital plane place at the edge-on and face-on geometry, the accuracy of the orbit determination results are relatively worse. The accuracy depends on not only the one-arc orbit determination accuracy and the spacecraft dynamics model error but also the small $\Delta V$’s prediction error. The next step is to improve the accuracy of the prediction and reconstruction of the small $\Delta V$’s caused by AMDs events.

Fig. 4. and Fig. 5. show the evolution of the perilune and apolune altitude of Okina and Ouna, respectively. After the successful lunar gravimetry observation, Okina made a impact with lunar surface on 12 February 2009. Ouna lasted its VLBI observation by the end of June 2009.

### 2.2 Extended Mission Phase

The Kaguya spacecraft made the shift to the extended mission phase in November 2008. In the initial plan, Kaguya maintain the same altitude orbit as the nominal observation orbit until the March 2009, and then descend to the low altitude orbit (about 50km) for additional scientific observation.

Unfortunately, in the end of December 2008, one of the three reaction wheels (RW) transited to the friction torque increasing state (Originally, Kaguya had four RWs, and one of the four RWs had already broken in July 2008) before the orbit transition from the nominal observation altitude to the
Fig. 3. Orbital Evolution of Kaguya

Fig. 4. Orbital Evolution of Okina

Fig. 5. Orbital Evolution of Ouna
low altitude orbit. Therefore, the attitude control mode changed from the RW mode to the thruster mode. This thruster attitude control method generate small translational acceleration for the same reason of AMD event, so we have to perform the orbit determination and orbit prediction under the thruster attitude control.

The Kaguya spacecraft usually maintained its +z axis toward the center of the moon direction to make scientific observation by means of various scientific instruments equipped on the spacecraft’s +z panel. The frequency of the thruster attitude control depends on the disturbance torque such as solar radiation pressure torque and gravity gradient torque. The configuration of the dead-band and attitude control accuracy were also affected the frequency.

Although, it is inefficient to consider the all thrust pulses with the same frequency of the actual spacecraft attitude control, it is very difficult to determine the spacecraft’s orbit without considering the small $\Delta V$’s. Therefore, we used coarse frequency small $\Delta V$’s model that accumulated the thruster events every 10 minutes. There are no dynamics model to estimate the all small $\Delta V$’s in the SELENE-FDS, thus we treated the small $\Delta V$’s as constant values and update its magnitude reflect the flight results.

The evolution of the perilune and apolune altitude of Kaguya during the extended mission phase are also shown in Fig. 3. We performed five altitude control maneuvers and maintain the low altitude orbit to make scientific observation in the specific region. For example, to observe the low altitude magnetic field over the South Pole-Aitken basin (SPA) by means of lunar magnetometer (LMAG), Kaguya was injected into 10×60 km altitude orbit.

Although, we obtained the tracking data during the low altitude phase, which will make a considerable contribution to the lunar gravity field estimation, the effect of the thruster attitude control complicate to use for the gravity analysis.

3. CONTROLLED LUNAR IMPACT

At the end of the extended mission, Kaguya made a controlled impact with the lunar surface. The impact point, altitude, and time are investigated with considering the detailed topography data. The lunar impact analysis and its operation results are discussed in this section.

3.1 Lunar Impact Analysis

To analyze the impact point, we used a global lunar topography data derived from SELENE laser altimeter (LALT). The spatial resolution is finer than 0.5 degree [5]. The 0.0625deg grid data were used in this analysis. The overview of the procedure of the lunar impact analysis are as follows; 1) to generate the orbital prediction ephemeris which include the impact orbit, 2) to compare the immediate beneath altitude of spacecraft calculated from the orbit prediction ephemeris and the height of lunar surface derived from lunar topography grid data, 3) to solve the impact time by using iterative method.

Before the controlled lunar impact operation of Kaguya, the relay sub-satellite Okina made a impact on the lunar far-side on 12 February 2009. Although, this is not a controlled impact event (i.e., Okina have no propulsion system and impact event was induced by the nature perturbation), the procedure of lunar impact analysis have a number of common points. This is a good opportunity for the preliminary practice for the lunar impact analysis of Kaguya. We performed lunar impact analysis for Okina before a few weeks ago the impact event and updated the expected time, impact point, velocity, and impact angle. The actual operation results were consistent with the preliminary analysis. We obtained a lot of knowledge and information that applicable to the Kaguya’s controlled impact analysis and operation. After the 11th altitude control maneuver, Kaguya orbited the low altitude orbit not previously experienced (perilune is about 10km). Although, the perilune
was placed at over the SPA which region is relatively low altitude, the highest altitude of the lunar topography is about 10.75km (-158.64E, 5.44N)[5] and higher than Kaguya’s perilune altitude. Therefore, we checked to be sure that the Kaguya do not impact unexpected time and point. We also checked the consistency of the orbit prediction ephemeris by comparing the predicted orbit and actual orbital evolution at daily operation.

In the case of the controlled impact, the effects of orbit determination error (OD error) as well as the ΔV execution error (DV error) are should be taken into account. The impact time is before the perilune passage time. The dispersion of the impact time and point are evaluated by using a Monte-Carlo analysis with considering the OD and DV error. Fig. 6. shows the dispersion of the impact points, with considering; a) both OD and DV error, and b) only OD error. The effect of DV error is dominant and if the magnitude of ΔV is small the altitude of the perilune does not descend and jump the first terrain which include the nominal impact point. In order to prepare the actual operation, especially for the tracking station arrangement, we also evaluated the effect of ΔV magnitude error (relatively large ΔV error including no ΔV execution case). The nominal impact point also varies with changes in the magnitude of small ΔV’s.

Fig. 6. Dispersion of Impact Points

Fig. 7. Orbital Evolution of Kaguya Around the De-orbit ΔV Execution
Fig. 7. shows the evolution of the altitude of Kaguya and the height of the lunar surface from the mean radius of the moon (1737.4km). The intersection of 2 lines means the impact time. The impact time is before the perilune passage time.

3.2 Operation Results

In the lunar impact operation, at first we performed the orbit determine for the orbital maneuver planning. After that, the impact information i.e., prediction impact point, time, velocity, and angle with respect to both terrain and horizontal surface are updated with acquiring the radiometric tracking data. The results of the lunar impact analysis were provide to the spacecraft operation team to use the actual operation. During the de-orbit ΔV execution, the radiometric measurements were acquired at Usuda Deep Space Center (UDSC) in real-time and evaluated whether go on as planned.

In order to estimate the actual impact point we performed orbit reconstruction analysis by using the 2-way Doppler data acquired during and after the de-orbit ΔV execution at UDSC. The de-orbit ΔV vector are treated as estimation parameters.

In addition to the radiometric tracking data, the LALT instrument measured the slant range from the spacecraft to the lunar surface. To verify the consistency of the results of orbit reconstruction analysis, we compare the computed range data derived from orbit reconstruction data and the actual LALT measurements. Fig. 8. shows the correlation of computed range and LALT measurements (red: actual LALT measurements, green: computed range based on the prediction ephemeris, blue: computed range based on the orbit reconstruction ephemeris). The orbit reconstruction data is good fit to the LALT measurements, and the orbit prediction data is also fit the LALT measurements. According to Fig. 8., Kaguya impacted near the nominal impact point.

We measured a loss of signal around 18:25 at UDSC and other GN. These observation results are consistent with the preliminary impact analysis. Fig. 9. shows the impact point and impact orbit of Kaguya derived from orbit reconstruction data. The Kaguya made a lunar impact at 18:25 June 2009 (UTC) near the Gill crater.

![Fig. 8. Correlation of Computed Range Data and LALT Measurements](image-url)
4. LUNAR GRAVITY FIELD ESTIMATION

We develop the lunar gravity field model (SELENE Gravity Model Tsukuba: SGMT) by using the tracking data of Kaguya and Okina, for the improvement of the orbit determination and prediction accuracy as well as for the scientific analysis usage (e.g., lunar interior structure analysis)[6]. The technique that to estimate the actual gravity field of the target body during its mission phase by using own tracking data is effective for the future solar system exploration mission. For example, the small body exploration mission that the gravity field model has relatively large uncertainties before the spacecraft rendezvous with its target body.
We used the tracking data of Kaguya and Okina for the lunar gravity field estimation. In particular, the 2-way S-band RARR (i.e., range and Doppler) measurements of Kaguya and Okina, and the 4-way Doppler measurements of Kaguya, respectively. Fig. 10. shows the selenographical coverage of the 4-way Doppler measurements. The lunar far-side is on the left side of the figure, and the lunar near-side is on the right side of the figure. The sparse region still exist at the northern hemisphere of the lunar far-side.
At this time, we developed several kinds of lunar gravity field models (e.g., no \textit{a priori} covariance constraint model, Kaula’s constraint [7] model, LP100J error covariance constraint [8] model, and hyperbola rule constraint model that newly-developed as a trial). The free-air gravity anomaly map of SGMT100 (Kaula’s constraint, degree and order 100 model), SGMT60 (no \textit{a priori} constraint, degree and order 60 model), and LP100J are shown in Fig. 11(a), Fig. 11(c), and Fig. 11(e), respectively. The error of free-air gravity anomaly map are also shown in Fig. 11(b), 11(d), and 11(f), respectively. It is clearly that the pattern of the gravity anomaly of located at the lunar far-side get better as compared with the LP100J. The error of free-air gravity anomaly map are also improved by including the SELENE 4-way Doppler measurements. We also attempted to estimate the SGMT100 without a priori constraints, it seems difficult to estimate from only SELENE tracking data.

The residuals of the 4-way Doppler measurements are shown in Fig. 12. Blue means LP100J (up to a degree and order 60 truncated model), and red means SGMT60, respectively. It is clearly that the residuals of 4-way Doppler measurements get smaller when we use the SGMT60. Although, the residuals of the 4-way Doppler measurements get smaller, from the point of view of the orbit determination and prediction accuracy, it has significant scope to continue to improve. At this time, the SGMT60 is better than LP100 (60th degree and order), but we cannot say for sure that SGMT100 is better than LP100 (100th degree and order) according to the results of the orbit determination and prediction analysis.

In order to improve the orbit determination and prediction accuracy, we are going to modify the spacecraft dynamics model and to investigate the arc length and weight. The improvement of each orbit determination accuracy may provide the improvements of gravity estimation accuracy. The next step is to include the remaining measurements e.g., the tracking data (RARR) of Ouna, the VLBI measurements of Ouna and Okina, and the tracking data of Okina that acquired at the low altitude orbit around the lunar impact operation of Okina.

5. SUMMARY

During the nominal mission phase, we performed the orbit determination and prediction for the
mission operation and initial scientific analysis. From the point of view of the mission operation, the orbit determination and prediction accuracy satisfy the mission requirement. Although, in the extended mission phase, the attitude control mode changed to the thruster mode that generate the frequent small $\Delta V$'s and have great influence on the orbit determination and prediction analysis, we overcome the difficult situation and could provide the acceptable orbit prediction ephemeris to use the mission operation.

We developed new lunar gravity field models by using Kaguya’s 2-way RARR, 4-way Doppler measurements, and Okina’s 2-way RARR measurements. The gravity fields of the lunar far-side is improved compared with the historical lunar gravity models. The additional gravity estimation analysis are now under way to achieve further improvement.

At the end of the mission, Kaguya made a controlled impact with the lunar surface. We performed precise impact analysis based on the global lunar topography data and led the successful return to the moon as planned. The technique to analyze the precise impact point and time with considering the actual lunar topography is useful for the future lunar exploration mission.

6. REFERENCES


