Study of Pitch Attitude Estimation Using a High-Definition TV (HDTV) Camera on the Japanese Lunar Explorer SELENE (KAGUYA)

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The lunar explorer SELENE (also called KAGUYA) carried thirteen scientific mission instruments to reveal the origin and evolution of Moon and to investigate the possible future utilization of Moon. In addition to the scientific instruments, a high-definition TV (HDTV) camera provided by the Japan Broadcasting Corporation (NHK) was carried on KAGUYA to promote public outreach. We usually use housekeeping telemetry data to derive the satellite attitude along with orbital determination and propagated information. However, it takes time to derive this information, since orbital determination and propagation calculation require the use of the orbital model. When a malfunction of the KAGUYA reaction wheel occurred, we could not have correct attitude information. This means that we don’t have a correct orbital determination in timely fashion. However, when we checked HDTV movies, we found that horizon information on the lunar surface derived from HDTV moving images as a horizon sensor was very useful for the detection of the attitude of KAGUYA. We then compared this information with the attitude information derived from orbital telemetry to validate the accuracy of the HDTV derived estimation. As a result of this comparison, there are good pitch attitude estimation using HDTV derived estimation and we could estimate the pitch angle change during the KAGUYA mission operation simplify and quickly. In this study, we show the usefulness of this HDTV camera as a horizon sensor.

Key Words: KAGUYA, Attitude Estimation, HDTV, SELENE

1. Introduction

The Japanese lunar explorer SELENE, nicknamed KAGUYA, was launched from the Japan Aerospace Exploration Agency’s (JAXA) Tanegashima Space Center on September 14, 2007, and impacted Moon on June 11, 2009. KAGUYA carried 13 scientific mission instruments to reveal the origin and evolution of Moon, and to explore the possibility of the future utilization of Moon1). In addition to the scientific instruments, a high-definition TV (HDTV) camera provided by the Japan Broadcasting Corporation (NHK) was carried on KAGUYA to promote public outreach. When a malfunction of KAGUYA’s reaction wheel occurred, we found that it was very useful to detect KAGUYA’s attitude by using horizon information on the lunar surface derived from the HDTV movie images. In general, Earth-orbiting satellites use a two-dimensional infrared and/or visible sensor as a horizon sensor along with star trackers and other Earth sensors to determine the satellite attitude operationally. In addition, a horizon sensor was mounted on the Mars Global Surveyor, and was proposed for lunar and other exploration missions. In a lunar mission, we usually use housekeeping (HK) telemetry data to derive the satellite attitude along with orbital-determination information, with observation information from star trackers. However, it takes time to derive this information, since orbital determination and propagation calculation require the use of the orbital model. The HDTV cameras were used to capture HDTV movie images of the lunar surface and Earthrises/sets above Moon, but in this study, we applied these HDTV movie images to determine the satellite attitude by using the lunar horizontal line number as a horizon sensor (since the HDTV camera shot the lunar horizon when shooting the Earthrise/set). This approach is a very simple and quick way of estimating satellite attitude changes in the pitch direction. Therefore, in this study, we estimated the pitch-angle changes during the KAGUYA mission operation, including under nominal operation, extended operation, and the reaction-wheel anomaly phase, by using HDTV moving images. We then compared this information with the attitude information derived from orbital telemetry information to validate the accuracy of the method2).

2. KAGUYA’S HDTV Camera Specifications

NHK developed a high-definition camera system, shown in Figure 1, to take high-definition still and moving images of the Earth rising from the lunar surface. This system enables compressed images to be shot using a small 2.2-million-pixel high-definition camera, and can record moving images for a maximum of 1 min on 1 GB of memory. Interval-record modes of 2×, 4×, and 8× are also available for shooting wider lunar surface areas in the along-track direction, in which 2, 4,
and 8 min of moving images are obtained at frame rates of 2/30, 4/30, and 8/30 s, respectively. For observation of the lunar surface, the HDTV wide-angle camera was in nominal operation in the 8× interval mode.\(^5\)

![HDTV camera](image1)

**Fig. 1.** KAGUYA outlook with an HDTV camera.

The fields of view (FOVs) of the telescopic camera and wide-angle camera are 15.5° × 8.7° and 50.1° × 29.5°, respectively, and the angles of incidence are 18.5° and 157.5°, respectively, from the +X-axis of the KAGUYA spacecraft to the nadir. The resulting best pixel resolution at an altitude of 100 km is about 130 m in the across-track direction and 460 m in the along-track direction, which is comparable with the Clementine UVVIS spatial resolution.

After the successful launch of KAGUYA, its HDTV camera captured the first moving image of the Earth at a distance of 110,000 km from the Earth on September 29, 2007. After being injected into a lunar polar orbit of about 100 km, the HDTV camera was in operation between October 28, 2007 and June 11, 2009. KAGUYA descended to lower than 50 km in February 2009.

### 3. Pitch-angle Change Estimation Using HDTV Camera

#### 3.1. Proposed estimation method

Since the HDTV camera shot the Earthrise and set over the lunar horizon with standard HDTV-quality movie images (1920 pixels × 1080 lines), the lunar horizon exists as the line around the center of the image during the nominal operation phase with KAGUYA at an altitude of about 100 km above Moon. This means that the HDTV camera can be used as a horizon sensor by using line number of the lunar horizon. This method is similar to generating a strip image from the line data of HDTV movie images at a given line. Figure 2 illustrates the KAGUYA HDTV observation geometry: Lu is the uppermost line of the HDTV camera, Lb is the bottom line of the HDTV camera, Lo is the nadir location of KAGUYA, and Lh is the line at the horizon point. Lu is line number 1080, and Lb is line number 1.

In general, KAGUYA flew over Moon with directing Z-axis instrument calibration during KAGUYA coastal flight operation, and the pitch angle with Lh was completely different from that under nominal operation. Figure 3 shows the location of Lh under nominal operation.

A pitch-angle change also occurred when the KAGUYA satellite attitude was changed (for example, when the attitude control method was changed). In addition, there was also some satellite attitude variation (including pitch-angle variation) because a predefined satellite attitude control rule was permitted within a certain attitude variation.

![HDTV observation geometry](image2)

**Fig. 2.** HDTV observation geometry.

Since there were more than 200 HDTV images, we developed automatic horizon-detection software. This software checks the digital count at 960 pixel points, from line 1 to line 1080, for all still images extracted from the HDTV movie images (e.g., about every 0.3 s for the 8× interval mode). The horizon is detected if the digital count is 30 counts greater than the previous line’s digital count and there are three digital counts within a 10-count variance.

Lh is computable as function of H by the use of trigonometry, where the satellite altitude H and lunar diameter R are given.

\[
\text{Lh-nominal} = \frac{\text{Ah}-\text{Ab}}{\text{Afov}} \quad (1)
\]

\[
\text{Ah} = 90 - \text{Bh} = 90 - \cos^{-1} \left( \frac{R+Lh}{R+H+hl} \right) \quad (2)
\]
where \( L_h \) is the line number at the lunar horizon, \( L_h \)-nominal is the line number at the lunar horizon with satellite altitude \( H \), \( A_h \) is the nadir angle at the lunar horizon line with satellite altitude \( H \), \( A_b \) is the nadir angle at the bottom of the field of view (FOV) of the HDTV camera (1080-line point), \( B_h \) is the nadir angle at the lunar horizon line from Moon’s center, \( B_b \) is the nadir angle at the bottom of the FOV of the HDTV camera from Moon’s center, \( A_{fov} \) is the nadir angle of the FOV of the HDTV camera (fixed number for wide and telescopic camera), and \( \Delta A_{fov} \) is delta of the nadir angle of the FOV.

\[
\Delta A_{fov} = \frac{A_{fov} - 1080}{(total \ number \ of \ lines)} \]

\( H \) is calculated by JAXA’s orbital data distribution system (http://odweb.tksc.jaxa.jp/odds/main.jsp), \( h_l \) is the elevation of Moon under the KAGUYA orbiter, and \( h_2 \) is the elevation of Moon at Moon’s horizon line as determined by KAGUYA HDTV.

Since Moon is not truesphere, the limb elevation effect should be evaluated to estimate the pitch-angle error. Therefore, using the KAGUYA laser altimeter measurement, the limb elevation effect was calculated. In the maximum case, it would be 2\(^\circ\) if the start point was the lowest elevation on Moon and the limb was the highest elevation. However, HDTV movie observation could not be carried out continuously between the lowest point and the highest point, so the limb elevation effect may be less than 1\(^\circ\) in the pitch-angle error estimation.

\[
\Delta L_h = L_h\text{-nominal} - L_h\text{-observed} \tag{3}
\]

The pitch-angle change is

\[
\Delta A_h = \frac{\Delta L_h}{\Delta A_{fov}} \tag{4}
\]

The proposed method for pitch-angle change detection using HDTV is summarized in the flow chart in Figure 4.

Using this method, we calculated the pitch-angle changes from November 2007 (first lunar shot by HDTV during initial checkout) to June 2009, when KAGUYA impacted Moon. Figure 5 shows the trend of the changes in KAGUYA pitch angle between 7:18:50 and 7:26:50 on December 21, 2008. During this observation, there were about 1741 still images (the HDTV camera shot the lunar surface every 3.75 s). The pitch-angle error means the difference in nadir angle (pitch angle) between \( L_h \)-nominal and \( L_h \)-observed. The trend of the pitch-angle error may be caused by the limb elevation effect, as seen in Figure 5. In addition, the error values in Figure 5 indicate the limb detection error obtained by the HDTV detection method; this error was due to continuous shadow areas on Moon.

![Fig. 4. Flow chart of proposed pitch-angle change estimation method by using HDTV still image.](image1)

![Fig. 5. Pitch-angle error estimation by using HDTV still image as lunar horizon sensor.](image2)

![Fig. 6. Pitch-angle error trend (triangle marks the explained attitude control method change from reaction wheel to thruster control at the end of December 2008 because of the malfunction of the reaction wheel).](image3)
Figure 6 shows the trend of the pitch-angle error for the start point of each HDTV observation between October 30, 2007 (beginning of nominal operation at 100-km altitude) and June 2009 (end of mission when KAGUYA main orbiter impacted Moon’s surface). Delta V maneuvers to maintain the nominal observation orbit were performed every two months from December 11, 2007 until December 26, 2008, just before the reaction-wheel trouble on December 29, 2008, and these maneuvers caused great attitude changes. Therefore, the pitch-angle error during Delta V maneuvers was about 2–3°, and this error value was two to three times greater than that at other times. In addition, in December 2008 and February 2009, we carried out some tests on reaction-wheel recovery and thruster control, and the pitch-angle error increased by more than 20°.

3.2. Orbital element determination (precise attitude error estimation)

For lunar surface observations from a lunar orbit, KAGUYA conducted lunar-center-pointing three-axis attitude control in the lunar orbit4). For attitude control, KAGUYA used the lunar orbital coordinates shown in Figure 7, in which the origin is the satellite’s center of mass, the +z-axis points toward Moon’s center, and the +y-axis points toward the orbit anti-normal. KAGUYA aligned its yaw axis to the +z-axis and its pitch axis to the +y-axis. To realize lunar-center-pointing attitude control, KAGUYA used a star tracker for attitude determination with respect to J2000 equatorial coordinates, and onboard orbit propagation to calculate the lunar orbital coordinates with respect to J2000 equatorial coordinates. For the performance of onboard orbit propagation, orbit parameters estimated by a orbit determined system were uploaded from the ground to KAGUYA twice a week. Figure 8 shows the data flow for the lunar-center-pointing three-axis attitude control5).

As shown in Figure 8, the attitude control error includes an onboard orbit propagation error. Since KAGUYA did not have a precise navigation sensor such as the GPS receivers used on Earth-observation satellites, the onboard orbit propagation error was relatively large among the causes of KAGUYA’s attitude error. In particular, after the reaction-wheel failure on December 26, 2008, KAGUYA controlled its lunar-center-pointing three-axis attitude by its thrusters, and as a result of transitional velocity increments due to thruster firing, the onboard orbit propagation error became very large, producing a very large attitude error.

To remove the onboard orbit propagation error, we generated the precise orbit propagation and recalculated the attitude error in the lunar orbital coordinates in post analysis. Figure 9 shows the data flow for the precise attitude error estimation.

3.3. Results comparison

In this study, we compared the pitch-angle change values obtained using HDTV movie images (section 3.1) and using the orbit determination calculation (precise attitude error estimation, section 3.2) during the reaction-wheel three-axis control phase and the reaction-wheel troubleshooting period. Figure 10 shows the pitch-angle error trend on December 21, 2008, when KAGUYA was operated using the reaction wheel. Because orbit determination was performed every minute and the HDTV camera observed the lunar horizon every 1/3.75 s, there is a temporal resolution difference between the methods, even though Figure 12 shows the HDTV data only for every
10 s (sampled from the HDTV original estimation). This means that the temporal resolution of HDTV estimation is 225 times better than that of the orbit determination method.

Figure 11 shows a comparison of the pitch-angle error between the HDTV estimation and orbital data estimation between November 7, 2008 and January 14, 2009. During the reaction-wheel operation period (until December 29, 2008), the error difference between the two values was less than a few degrees. For instance, on November 7, the pitch-angle error by HDTV was 0.2° and that by orbit determination was 0.46°, as shown in Figure 11.

During the reaction-wheel operation period, the orbital determination error was relatively small, and the propagation accuracy improved during nominal operation and the early extended phase after adjustments in the initial checkout period (between December, 2007 and December 29, 2008). In contrast, there was a big difference between the two values during the reaction-wheel troubleshooting period from December 29, 2008 to March 26, 2009. Between December 30 and January 9, there was a big difference between the two values because of an attitude information determination error in the orbit determination information, with a large error in propagation accuracy during the reaction-wheel recovery testing, as shown in Figure 12. However, on January 10, after adjustment of the orbit determination parameters, the pitch-angle error values were almost the same (also shown in Figure 12).

After the malfunction of the reaction wheel, the pitch angle was also affected by yaw- and roll-angle variation. However, these angle variations were less than 10°, and the limb elevation difference was less than 0.5 km within a 10° longitude change. This caused a pitch-angle error of less than 0.1°, so these effects were ignored.

Therefore, in general, these results show consistency between the HDTV-estimated value and the orbital-determination value (except for the adjustment time needed for orbital-determination estimation), and both the accuracy and usefulness of using HDTV images as a horizon sensor are verified. In addition, when we applied the HDTV
In this study, we also found that there are two limitations of this HDTV estimation method. The first is that this method is only useful for detecting a horizon line when the HDTV movie images are shot in the daytime area, because the change in count value from deep space in the night area of Moon is not large. In addition, even if the HDTV camera was used to shoot the daylight lunar surface area, misdetection by HDTV still occurs when using still images because of shadow areas. In the polar regions especially, there are permanent shadow areas that were revealed by KAGUYA scientists, and there is a large error in the detection of the lunar horizon if a permanent shadow area is located at the center of the pixel of the HDTV still image when using the proposed HDTV method. Another limitation is that there is no chance to detect the horizon line when HDTV images are shot only on the lunar surface instead of from deep space, such as from coastal flights or KAGUYA flights with large, positive pitch-angle errors.

4. Conclusion

This study has shown the consistency of pitch-angle error values obtained by simple HDTV estimation and orbital-determination estimation, which were within 1° during the reaction-wheel operation period and within 3° during continuous thruster operation mode from January 2009. This result illustrates the usefulness of an HDTV camera as a horizon sensor for detecting attitude changes. To increase the observation chances of areas of interest, it is very important to obtain attitude information as soon as possible. Thus, horizon detection using a movie camera is the only positive solution for providing pitch-angle attitude information in near real time.

Acknowledgments

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References

3) Honda, R.: Results of high-definition television system (HDTV) on board SELENE (KAGUYA), LPSC40 (2009).
5) Matsumoto, S.: Operation and Evaluation Results of KAGUYA Attitude and Orbit Control System on Lunar Orbit, ISTS 27 (2009), 2009-d-06.