Development of the KAGUYA (SELENE), a Lunar Orbital Spacecraft

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Abstract

Beginning with the "one small step" of commander Armstrong of Apollo 11 in 1969, manned lunar exploration had been halted since Apollo 17 in 1972. In September 14, 2007, Japan restarted a new lunar exploration activity by launching the lunar orbital spacecraft SELENE (KAGUYA).

This paper introduces the main specifications of the KAGUYA mission for which NEC acted as the prime coordinator, being in charge of the mission from the development to the operational stages. The operational process from the launch to the end of the mission is also discussed, together with the technology used in the laser altimeter that has also been developed by NEC.

Keywords

lunar exploration, SELENE, KAGUYA, Rstar (OKINA), Vstar (OUNA)
orbit maneuver, lunar landing, laser altimeter

1. Introduction

The KAGUYA or SELENE (SELenological and ENgineering Explorer) was launched by the 13th model of the H-IIA launch vehicle on September 14, 2007. It was the most important lunar exploration mission since the Apollo project. After being injected successfully into lunar orbit on October 4, the spacecraft reached the observation orbit, which is a circular lunar orbit (polar orbit) at an altitude of 100 km and with an orbital inclination of 90°. It also succeeded in injecting the two sub-satellites for lunar gravity field measurement (relay satellite Rstar, or OKINA, and VRAD satellite Vstar, or OUNA) into their designated orbits during its orbit transfer from the extended elliptical orbit to the circular orbit.

The KAGUYA performed 14 observation missions from its orbit at a 100-km altitude and acquired much data required for the elucidation of the origin and evolution of the Moon. The lunar and gravity field maps thereby created using the altimeter data are now published in the textbooks of elementary and high schools and some of the results even challenged established theory on the evolution of the Moon. The impressive images recorded with the HDTV camera were also applauded by their many viewers.

From an engineering viewpoint, the mission succeeded in verifying the key technologies required to support the planned lunar orbit spacecraft to follow, such as the Asia-first satellite delivery into lunar polar orbit and the implementation of triaxial attitude control on lunar orbits.

2. Outline of the KAGUYA, SELENE

The KAGUYA is composed of three satellites including the main orbiter and two sub-satellites (Rstar and Vstar) and the total weight at the time of the launch was 3,020 kg (including 1,120 kg of propellant). This is a large satellite with a single-wing canted solar array paddle (generating 3,500 W power), a deployable biaxial gimbal, high-gain antenna with a 1.6-m diameter and bipropellant 500-N main engine (OME: Orbit Maneuvering Engine) for use in the precise injection into lunar orbit.

Table 1 shows the main specifications of the KAGUYA satellite system and **Fig. 1** shows its external view on circular lunar orbit. Each sub-satellite weighs about 57 kg and has an octagonal pole shape with approximate dimensions of 1 × 1 × 0.65 meter. The outer surfaces of the octagonal pole are the solar cell panels generating power of about 80 watts.

After the main orbiter has entered the circular lunar orbit at 100-km altitude, it deploys a lunar magnetic field observation antenna of about 12-meters length and lunar radar sounder antennas (×4) each of about 16-meters length. After deployment of all antennas, the overall system size on orbit is about 23 × 24 × 3 meters.

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Table 1 Main system specifications of the KAGUYA.

Category	Item		Specifications
Overall system	Launch vehicle		Single launch using H-IIA
			Fairing: 4S type
			PAF: 2360SA
	Mass		Main orbiter: 1,791 g
			Relay satellite: 57 kg
			VRAD satellite: 57 kg
	Generated power	Main orbiter	Solar angle, best: ≥3,260 W Solar angle, worst: ≥1,831 W
		Relay satellite	Generated power: ≥69.5 W
		VRAD satellite	Generated power: ≥66.0 W
Main orbiter orbit	Observation orbit		Orbit altitude: 100 km ±30 km
			Orbital inclination: 90° circular lunar orbit
			Orbital period: Approx. 118 min.
	Attitude control	Lunar orbital observation attitude	Lunar center-pointing three-axis attitude control
		Yaw around maneuver	Yaw around maneuver at β = 0° (max. twice an year)

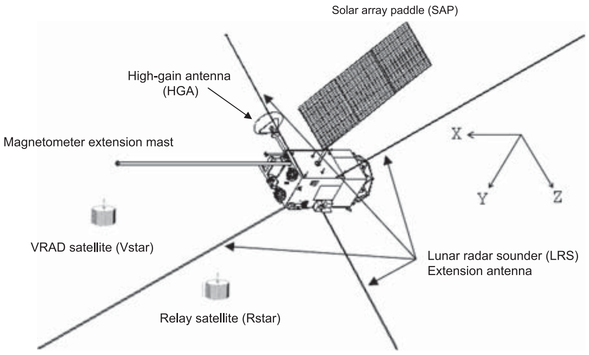

Fig. 1 On-orbit configuration of KAGUYA.

The main features of the KAGUYA are as follows.

(1) The center of mass

The solar array paddle and high-gain antenna of the KAGUYA are installed asymmetrically. In order to deal with any deviation in the center of mass caused by separation of the sub-satellites or consumption of the propellant, we adopted measures to accurately set the OME installation position and the cant angle as well as applying the torque arms of the control thrusters.

(2) Heat radiation design

Under regular operational conditions, the KAGUYA orbits the Moon while facing the +Z-plane toward the lunar surface between the solar light and the solar-irradiated lunar surface areas. The lunar surface temperature may be up to +120°C.

To ensure the requisite heat radiation performance and reduce the heater power during a lunar eclipse, we restricted the heat radiation surface to the +Y-plane and installed nine thermal louvers.

(3) Bus/mission shared high-gain antenna (HGA)

The high-gain antenna is installed on the Z-plane that is permanently facing the opposite direction to the lunar surface. To enable communications with the Earth, it is always oriented toward the Earth by driving the biaxial gimbal mechanism via signals from the attitude/orbit maneuver system. When the satellite enters the far side of the Moon as seen from the Earth, the high-gain antenna is oriented toward a sub-satellite and is deployed for gravity field measurements using the 4-way Doppler method.

(4) Power circuit management design

The solar array with a cant angle of 30° is set to the optimum angle according to the relationship between the solar light incident angle and the 100% sunlit orbit and a yaw around maneuver (inversion of traveling orientation) is performed every six months to reserve the required power. Although the KAGUYA carries a battery with a capacity of about 5,500 Wh (fully charged,) the battery would be exhausted when the phase between the shadow of the Earth and that of the Moon is in the worst condition, i.e. during a lunar eclipse (a phenomenon in which both the Moon and satellite are inside the shadow cast by the Earth). To prevent such an occurrence by operational considerations, the phase adjustment operation (orbit adjustment, maneuver) is executed about a month before lunar eclipse in order to minimize battery discharge.

(5) Electromagnetic compatibility design

Since a requirement of the mission is to observe faint radio waves, a noise filter is added and the harnesses are shielded to minimize the level of field-emission noise emitted by the KAGUYA. As a result, the satellite achieves quietness below -20 dB (1/10) of the MIL standard in the frequency domain below 30 MHz. In the 5-MHz domain, which is at the center of the frequency of observation, the quietness is as low as about -60 dB (1/1000) of the MIL standard with reference to the observation equipment GND.

(6) Magnetism control

The magnetic field of the Moon is only 1/100,000 that of the Earth. With the KAGUYA, the magnetism produced by the satellites should be minimized in order to measure such a low lunar magnetic field. For this purpose, we have taken measures that include the installation of magnetic shields, cancellation magnets and cancellation loop wiring, etc., and have succeeded in meeting the requirements of the observation equipment.

3. Lunar Orbital Transfer and Lunar Orbital Injection

(1) Lunar orbital transfer operation

There are several lunar transfer orbits that can be taken to reach the Moon from the Earth. For the KAGUYA, we adopted the phasing orbit that orbits the Earth by 2.5 turns because this method can deal flexibly with unexpected events. For the lunar transfer orbit phase we twice performed orbit maneuver using the OME and three times for orbit maneuver using four 20N thrusters. **Fig. 2** shows the orbit maneuver sequence and **Table 2** shows how the maneuvers were achieved. With the orbit maneuver, the start time and amount of acceleration are set via commands and firing is stopped automatically based on the on-board accelerometer data. In spite of anxiety concerning the noise of the accelerator, we were able to control the orbit with high accuracy. An acceptable small error only was estimated from the orbit determination values obtained after the completion of the orbit maneuver procedures.

(2) Lunar orbit insertion operation

When the satellite approaches the synodic conjunction point with the Moon, its velocity is increased by the gravitational pull of the Moon. When the satellite reaches the closest point to the Moon, the OME is fired for a long period to decrease the velocity. This causes the satellite movement to be balanced with the gravitational pull from the Moon so the satellite starts to orbit the Moon.

This operation is called the "lunar orbit insertion maneuver." If this fails, the satellite would advance in an unintended direction away from the Moon. Although it was the most difficult operation with the KAGUYA, the difficulty was overcome and the extended elliptical lunar orbit was entered successfully. Subsequently, the two sub-satellites were separated and orbit maneuver was performed five times using the OME and three times using the 20N thrusters, and eventually the circular orbit was entered at 100-km altitude. The error between the planned and achieved maneuvers was below 1% (**Table 3**). The saving in the consumed propellant thanks to the highly accurate orbit maneuvers will enable significant economies in subsequent missions.

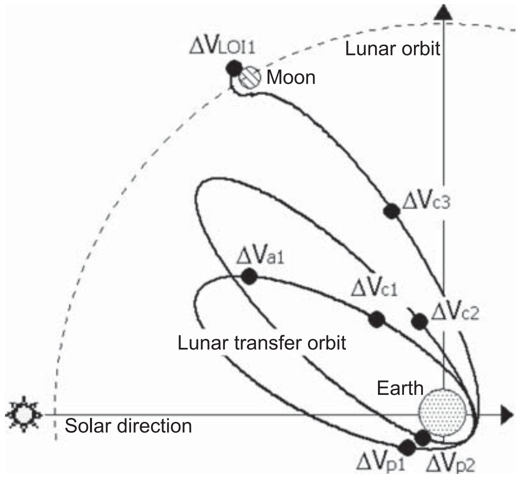

Fig. 2 Orbit maneuver sequence for lunar transfer orbit.

Table 2 Lunar transfer orbit maneuvers achieved.

Orbit maneuver name	Thrusters used	Firing time achieved [sec.]	Acceleration achieved [m/sec.]	Acceleration error [m/sec.]
ΔVc1	500N	118	23.57	0.39
ΔVa1	20N	37	0.77	0.19
ΔVp1	500N	484	93.57	0.14
ΔVc2	20N	57	1.23	-0.02
ΔVp2	20N	81	1.69	-0.01

ΔVc1: Orbit insertion error correction maneuver
ΔVa1: Orbit maneuver error correction maneuver
ΔVp1: Period adjustment 1 maneuver
ΔVc2: Period error correction maneuver
ΔVp2: Period adjustment 2 maneuver

Table 3 Lunar orbit insertion maneuvers achieved.

Orbit maneuver name	Thrusters used	Firing time achieved [sec.]	Acceleration achieved [m/sec.]	Acceleration error [m/sec.]
LOI1	500N	1,460	298.43	0.36
LOI2	500N	469	102.19	0.30
LOI3	500N	670	151.51	-0.09
LOI4	500N	656	164.68	0.26
LOI5a	20N	253	68.48	0.18
LOI5b	20N	1,013	25.74	0.12
LOI5c	20N	983	25.30	0.13
LOI6	20N	497	12.82	0.11

4. Regular Operation and Controlled Impact Operation

(1) Regular operation

After insertion in the lunar polar orbit at a 100-km altitude, the KAGUYA performed on-orbit checks for six weeks and then proceeded to the regular observation operation, in which 14 kinds of lunar exploration missions and image capturing using the HDTV camera were carried out. As HDTV camera images such as the “Earth rise image” and the 3D image of the Tycho crater shot with the terrain camera can be viewed on the website of the Japan Aerospace Exploration Agency (JAXA), we introduce below the bus operations achieved during the regular observation operation.

With the lunar orbit at a low altitude of 100 km, the orbit tends to present extremely complex behavior due to the significant effects of the asymmetry of the lunar gravity field. The orbit maneuver must also be performed accurately because of the exploration mission to capture images of the whole of the sunlit area of the Moon without missing any part.

In addition, on the boundary with β angle of 90°, there are a large number of operational events to be performed, including the inversion of the solar array paddle rotation direction, the survival operation during lunar eclipse and the yaw around maneuver operation. These operations were executed via commands from the SELENE Mission Operation and Analysis Center that had been installed at the JAXA Sagamihara Campus.

(2) Controlled impact operation

After about seven months of post-term operation, we performed a controlled impact of the satellite using the small amount of propellant that remained. This operation aimed at learning the technique for dropping the satellite precisely on target, which was expected to provide useful experience that could be applied to support future lunar landing technology. The target impact point was selected to meet the following conditions; 1) it should be located in the shadow area on the near side of the Moon that could be viewed from the Earth so that the light emission accompanying the crash could be confirmed, and; 2) the satellite should approach the moon through the sunlit area until immediately before impact so that clear camera images would be obtained. Consequently, we performed a controlled impact operation on June 11, 2009, by setting the target location near to the Gill crater as shown in **Fig. 3** and we were successful in achieving impact at the targeted location. The light emission accompanying the crash was confirmed from several locations inside and outside Japan.

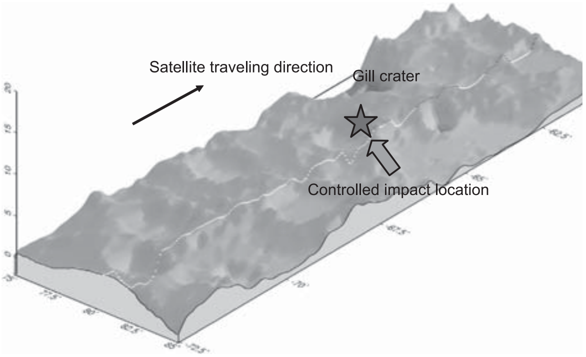

Fig. 3 KAGUYA’s controlled impact location.

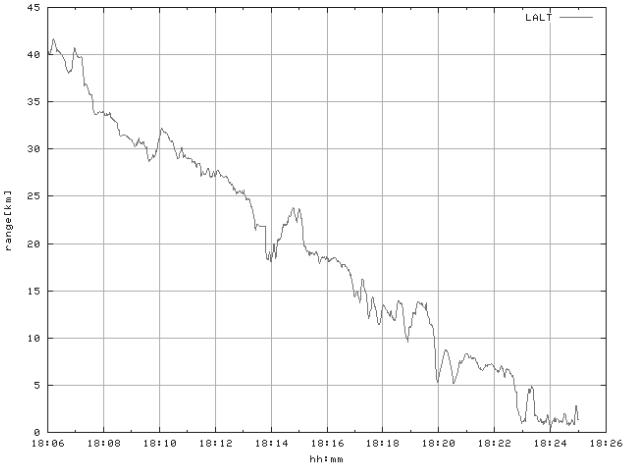

Fig. 4 Laser altimeter data during controlled impact.

Fig. 4 shows the data of the laser altimeter during the controlled landing operation. This clearly indicates a gradual decrease in the distance from the KAGUYA to the lunar surface as well as the altitude variations due to the presence of craters. The laser altimeter is a sensor developed by NEC and its results provided not only a successful preparation for a map of the whole lunar surface but also included valuable data that will serve lunar landing missions of the future. Details of the laser altimeter are discussed in section 5 below.

5. Laser Altimeter Technology

The laser altimeter (LALT, **Fig. 5**) emits laser light from the KAGUYA to the lunar surface and measures the distance by metering the round-trip time until the light reflected by the lunar surface returns to the KAGUYA. The device measures the

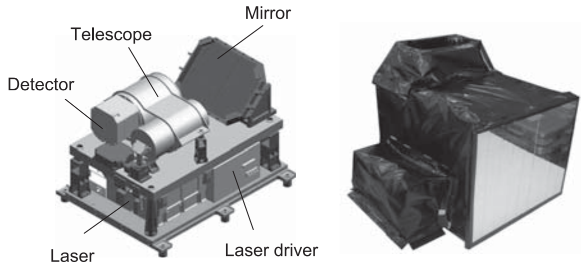

Fig. 5 External view and internal structure of the LALT.

altitude every second, and the altitude data of the entire lunar sphere obtained during the operation is used to draft a lunar topographic map. The laser altimeter acquired data that had not been available before the KAGUYA mission, including altitude data of the lunar polar-regions and details of the topography inside craters that had never been lit by the solar light.

The temperature of the LALT on lunar orbit is controlled using a heat radiation surface and heaters for dealing with temperature variations. The performance of the optical equipment including the laser deteriorates even by the smallest structural distortion due to temperature change. Therefore, the thermal and structural designs of the LALT incorporate various measures for preventing the influence of thermal distortion on the performance. To measure the complicated topography without missing anything from the altitude of 100 km, the LALT adopts a high-power laser and high-sensitivity detectors so that even the light reflected from inclined planes can be detected. The LALT also incorporates a counter circuit capable of measuring the lunar surface distance with a resolution of 1 meter, various laser driver circuitry and optical systems. Designed to withstand the H-IIA launch environment and the operating environment on the lunar orbit, it was mounted on the KAGUYA only after passing extended evaluation testing on the ground.

The LALT of the KAGUYA allowed us to verify the technologies required for the laser systems for space use including those suitable for lunar and planetary explorations.

6. Conclusion

For the lunar explorations of the future, the final report of the Council on Lunar Exploration held by the Strategic Headquarters for Space Development of the Japanese Cabinet Secretariat and compiled in June 2010 proposes to perform soft landing and robot exploration in the next lunar exploration mission scheduled for 2015. NEC wishes to maintain participation in the lunar exploration projects as the core activity of the science and technology development group by utilizing/advancing the lunar/planetary exploration know-how that has been cultivated over 25 years, since the Halley’s Comet mission “SAKIGAKE.” We aim to continue our activities in this field via our ongoing contributions to the work of the leading Japanese science foundations.

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