In-Space Performance of "KAGUYA" Lunar Explorer Propulsion Subsystem

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Abstract

"KAGUYA" (SELENE) is a Japanese Lunar Explorer launched by H-IIA rocket from Tanegashima Space Center on 14 September 2007.

The dual-mode bipropellant propulsion subsystem of KAGUYA includes two fuel tanks, an oxidizer tank, propellant and pressurant control components, twelve monopropellant 20N thrusters, eight monopropellant 1N thrusters, and a bipropellant 500N Orbit Maneuver Engine (OME).

Once the KAGUYA separated from the rocket, it circled the Earth twice and traveled to the Moon, where it entered lunar orbit. All maneuvers were performed through multiple 500N OME / 20N thruster firings.

This paper describes the in-space performance of KAGUYA Lunar Explorer bipropellant propulsion subsystem.

1. Introduction

The major objectives of KAGUYA mission are global observation of the Moon to investigate its origin and evolution. Furthermore, KAGUYA observes the distribution of the elements and minerals on the surface, topography, geological structure, gravity field, magnetic field remnant, and the environment of energetic particles and plasma of the Moon. The scientific data are also used for assessing the possibility of future utilization of the Moon.

In addition, JAXA also establishes the basic technologies for future Moon exploration; lunar polar orbit insertion, 3-axis attitude control and thermal control in a lunar orbit.

Moreover, KAGUYA takes pictures and movies of the Earth-rise from the Moon horizon.

Table 1 shows the main characteristics of KAGUYA.

KAGUYA consisted of the Main Orbiter and two small satellites (Relay Satellite and VRAD Satellite) which were attached on the Main Orbiter at launch. The Main Orbiter has a propulsion system, but the small satellites do not. They were launched together, orbited the Earth two and half times and reached the Moon vicinity. KAGUYA was first placed in an elliptical and polar orbit with a perilune altitude of 100 km; it later descended to its apolune altitude.

The Relay Satellite was separated in an elliptical orbit with an apolune altitude of 2400 km; the VRAD Satellite was separated at apolune altitude of 800 km.

The Main Orbiter was placed into a circular polar orbit at an altitude of 100 km; it surveyed the entire Moon for about one year.

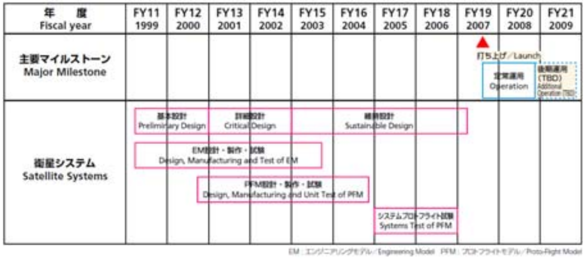
Figure 1 presents the KAGUYA development schedule.

The development started in 1999, systems integration and proto-flight testing performed at JAXA Tsukuba Space Center and launch operations including the propellant loading performed at JAXA Tanegashima Space Center.

Table 1 Main Characteristics of KAGUYA

Main Orbiter	Mass	3.0 tons
	Max Power	3.5 kW
	Size	2.1m×2.1m×4.8m
	Attitude control	Three- axis stabilized
	Orbit	Circular orbit, Inclination: 90°, Altitude : 100 km
	Mission period	1 year at mission orbit
Relay Satellite (Rstar)	Mass	50 kg
	Size	1.0m×1.0m×0.65m
	Attitude stabilization	Spin- stabilized
	Initial Orbit	Elliptical orbit, Altitude : 100 km×2400 km
VRAD Satellite (Vstar)	Mass	50 kg
	Size	1.0m×1.0m×0.65m
	Attitude stabilization	Spin-stabilized
	Initial Orbit	Elliptical orbit, Altitude: 100 km×800 km

Figure 1 Development Schedule



KAGUYA was launched by H-IIA rocket from Tanegashima Space Center on 14 September 2007.

It was subsequently injected into its required trajectory using the H-IIA rocket's second stage. After separation from the second stage, the KAGUYA onboard propulsion system despun KAGUYA and trajectory correction maneuvers put KAGUYA on target for a successful moon encounter which occurred on 4 October 2007. To date, the propulsion system has performed remarkably well; it has consumed much less propellant than pre-launch models had predicted. Based on the first year of in–space operation, the KAGUYA propulsion system is prepared to support the scientific mission at the moon.

Figure 2 portrays KAGUYA Mission Trajectory. Table 2 shows KAGUYA main events.

Once KAGUYA was separated from the rocket, it circled the Earth twice and then traveled to the Moon; it then entered a lunar orbit. All maneuver were performed using multiple 500N OME / 20N thruster firings.

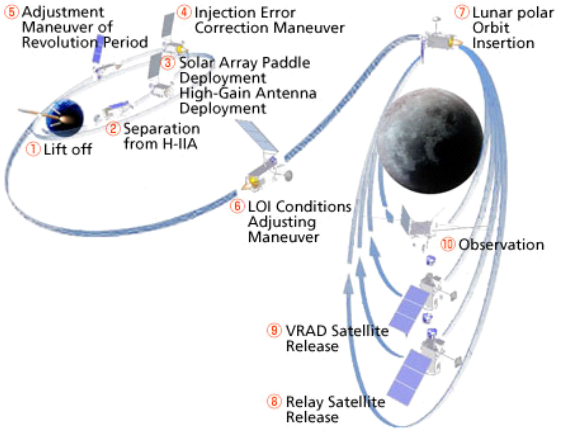


Figure 2. KAGUYA Mission Trajectory

Table 2 KAGUYA Main Events

Operational phase			Contents	Events
Launch preparation stage			From the start of launch preparation tasks to completion of preparation	Start of countdown
Launch stage			From completion of launch preparation to satellite separation after the Moon transfer orbit throwing	Lift off Nose fairing open 2nd stage separation Lunar transitional orbit insertion
Early stage	**Critical phase**	**Lunar transitional Orbit phase**	From satellite separation to Lunar polar orbit insertion (After approximately 1 h)	Separation from H-IIA Solar Array Paddle Deployment High-Gain Antenna Deployment Injection Error Correction Maneuver Adjustment Maneuver of Revolution Period LOI Condition Adjusting Maneuver
		Lunar polar Orbit phase	From Lunar polar orbit insertion to observation (After approximately 45 days)	Lunar polar Orbit Insertion Relay Satellite Release VRAD Satellite Release Orbit Correction Maneuver(six times) Observation
	Early operational phase		From completion of Lunar polar orbit insertion to completion of observation preparation	Observation equipment check out
Constancy phase			From completion of early operation to end of observation (10 months after the completing the early use)	Scientific observation HDTV shooting

2. Propulsion System

Figure 3 and Table 2 show schematic and main characteristics of the KAGUYA dual mode Unified Propulsion System (UPS).

The design of KAGUYA UPS was based mainly on the chemical propulsion system of "KODAMA" (Data Relay Test Satellite : DRTS) which is a geostationary satellite. The KAGUYA UPS consists of eight 1N attitude control monopropellant thrusters, twelve 20N attitude control and ΔV monopropellant thrusters, a single 500 N ΔV bipropellant thruster, two hydrazine (fuel) tanks, a single MON-3 (oxidizer) tank, two helium pressurant vessels and components necessary to control the flow of propellant and to monitor system health and performance.

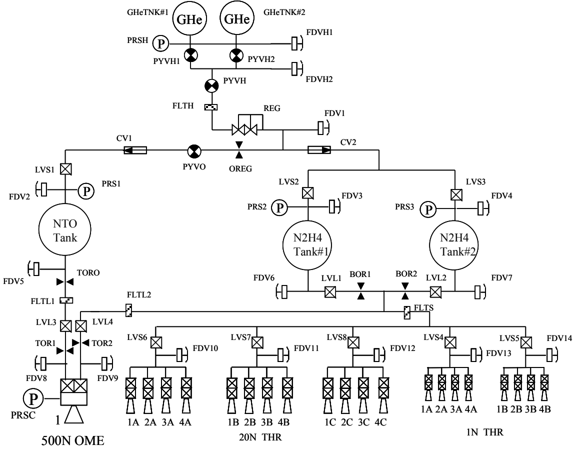


Figure 3 KAGUYA UPS Schematic

Table 3 KAGUYA UPS Main Characteristics

Item		Performance	Note
500N OME		Thrust 547 +54/-58 N Isp 319.8±5.1 s	Preg= 1.77 MPa
20N Thruster	Continuous Firing	(1) @OME Firing Thrust 14.2 +1.3/-1.5 N Isp >223 s (2) @20N×4 Firing Thrust 14.9 +1.3/-1.5 Isp >223 s	Preg= 1.77 MPa
	Impulse Bit	Minimum ON Time 31 ms Maximum 0.52 Ns	
1N Thruster	Continuous Firing	Thrust 0.68 +0.12/-0.13 N Isp >205 s	Preg= 1.77 MPa
	Impulse Bit	Minimum ON Time 20 ms Maximum 0.02 Ns	
Maximum Propellant Mass		N2H4 825+0/-135 kg MON-3 355+0/-30 kg Helium 5.4 kg	@20°C
Unavailable Propellant Mass		N2H4 <10.6 kg MON-3 < 6.2 kg	@20°C
MEOP		High Pressure Line 23.0 MPa Low Pressure Line 2.16 MPa Pc Sensor Line 1.03 MPa	
Proof Pressure		Fuel/Oxidizer Tank 1.25×MEOP Except Fuel/Oxidizer Tank 1.5×MEOP	
Burst Pressure		Fuel/Oxidizer Tank 1.5×MEOP Except Fuel/Oxidizer Tank 2.5×MEOP	
Mass (Dry)		151.85 kg	
Electrical power		<179.8 W	
Life time		1 year 1 month	

2.1. Tanks

The hydrazine propellant and helium pressurant are stored in two IA(IHI Aerospace Co. Ltd.) 429.3 liter titanium tanks with propellant management device (PMD) and a bulkhead. The bulkhead divides the tank interior so that the hydrazine moves in a smaller area on observation lunar orbit.

The MON-3 oxdizer and helium pressurant are stored in a IA 289.9 liter titanium tank with start basket.

The helium pressurant is stored in two ATK 67.3 liter titanium-lined, graphite-epoxy-overwrapped composite tanks.

2.2. Engine and Thrusters

(1) OME

A single IA 500 N ΔV bipropellant OME was developed and used for KODAMA as an Apogee Kick Engine (AKE). The OME has two injector heaters, designated “primary” and “redundant”. These heaters raise the temperature of the injector above the required minimum value of 20ºC to ensure that fuel hydrazine is not frozen when propellant flows through it and burns in the OME combustion chamber.

(2) 1N thrusters

Eight IA NDBF02003G01,G02 1N attitude control monopropellant thruster modules are used for KODAMA, KIRARI (OICETS), KAKEHASHI (COMETS), MIDORI (ADEOS), etc. One 1N thruster has two catalyst bed (catbed) heaters. The catbed heaters raise the temperature of the catalyst bed above the required minimum value of 200ºC to ensure that the catbeds are not damaged when propellant flows through them and decomposes catalytically. The valve heater maintains the temperature of the valve between the required minimum value of 5ºC and maximum value of 121ºC to ensure that hydrazine is not frozen and that the valve seats are not damaged.

(3) 20N thrusters

Twelve IA NDBF02004G01 20N attitude control and ΔV monopropellant thruster modules are used for KODAMA, etc. A 20N thruster has two catbed heaters and a valve heater. The catbed heaters raise the temperature of the catalyst bed above the required minimum value of 30ºC to ensure that the catbeds are not damaged when propellant flows through them and catalytically decompose. The valve heater maintains the temperature of the valve between the required minimum value of 5ºC and maximum value of 121ºC to ensure that hydrazine are not frozen and the valve seats are not damaged.

(4) Coordinate System and Thruster arrangement

Figure 4 shows KAGUYA coordinate system; Figure 5 displays the thruster arrangement from –X directions. All thruster locations and orientations are identifiable. The alignment of all thrusters and engine were measured prior to launch.

Table 4 shows the thruster firing matrix.

2.3. Latch Valves

The KAGUYA UPS contains four MOOG C18492-001 6/16 inch torque motor type latch valves and eight IHI/MOOG JAPAN N1045/101-02 4/16 inch torque motor type latch valves, plumbed as shown in Figure 3. The latch valves upstream thrusters are arranged such that a single thruster branch might be isolated (to isolate a leaking thruster, for example) while still maintaining the maximum number of usable thrusters. The system is designed such that the spacecraft maintains control on all three axes even if an entire thruster branch (i.e. the set of thrusters downstream of a single latch valve) is lost.

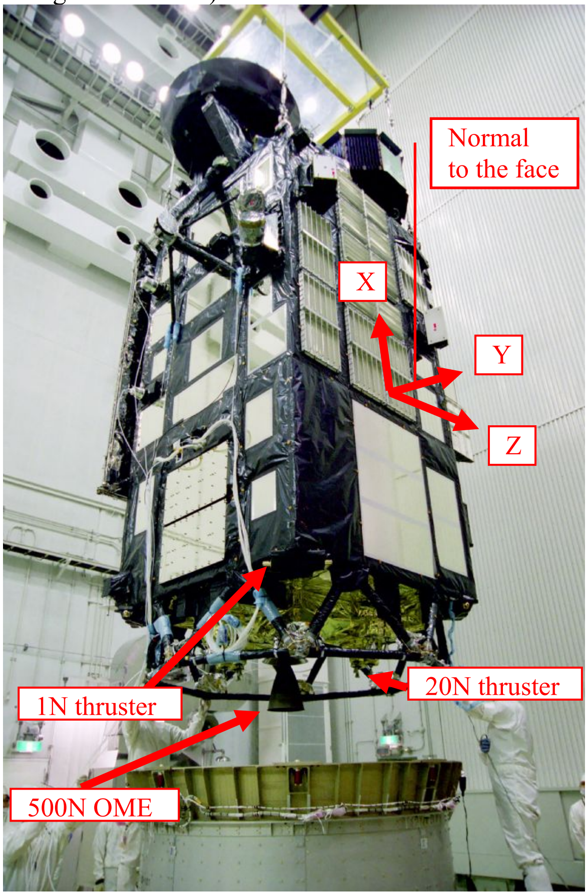
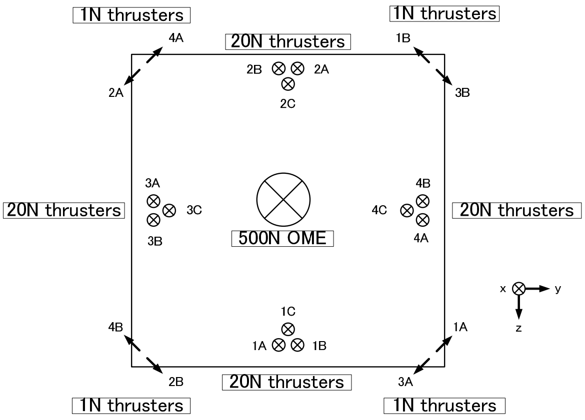


Figure 4 KAGUYA Coordinate System



Bottom View

Figure 5 Thruster Locations and Orientations

Table 4 Thruster firing matrix

mode	control		500N	1N thruster A				1N thruster B				20N thruster A				20N thruster B				20N thruster B			
				1A	2A	3A	4A	1B	2B	3B	4B	1A	2A	3A	4A	1B	2B	3B	4B	1C	2C	3C	4C
OME firing	ΔV		S																				
	roll	+		D	D			D*	D*														
		-				D	D			D*	D*												
	pitch	+										T				T				T			
		-											T				T				T		
	yaw	+												T				T				T	
		-													T				T				T
20N firing Settling	ΔV											F	F	F	F	F*	F*	F*	F*				
	roll	+		D	D			D*	D*														
		-				D	D			D*	D*												
	pitch	+											●				●*						
		-										●				●*							
	yaw	+													●				●*				
		-												●				●*					
Thruster control Unloading	roll	+		D	D			D*	D*														
		-				D	D			D*	D*												
	pitch	+										S				S#				S*			
		-											S				S#				S*		
	yaw	+												S				S#				S*	
		-													S				S#				S*

(1) S: 1 thruster firing D:2 thrusters firing T: 3 thrusters firing F: 4 thrusters firing ●: Off pulse firing
(2) * :backup
(3) # : nominal thrusters after checkout phase

2.4. Other Components

Other components include the following: a CARLETON B41569-3 series redundant pressure regulator which was used for KODAMA, two VACCO high pressure fill & drain valves, eleven IHI/SHIMAZU gas / fuel fill & drain valves, three IHI/SHIMAZU oxidizer fill & drain valves which were used for KODAMA etc., two CONAX 1801-096 Normally Close (NC) pyrovalves, two CONAX 1832-202 Normally Open (NO) pyrovalves, two VACCO single seat type check valves which were used for KIKU8(ETS-8), a WINTEC 12267-530 high pressure 4/16 inch filter which was used for KODAMA etc., a WINTEC 15241-722-5 low-pressure 4/16 inch filter which was used for KODAMA, two IHI/KOITO 85000-40001 6/16 inch filters which were used for KODAMA, etc; and five TABER Pressure Transducers. All these components have flight heritage.

3. Propulsive Events

Since launch, 13 maneuvers have been executed successfully to support spacecraft operations. This section will describe the typical cases, detail how the UPS was used, and present supporting data where appropriate.

3.1. During Launch

KAGUYA was launched with propellants only flowed to the latch valve seals. The remainder of the propulsion manifold was filled with helium. Figure 6 portrays pre-launch pressure. The pressure in the regulator was set a lower value because of the valve restriction under the flight mechanical environment. The catbed heaters for all the thrusters were powered on before launch to protect the catbeds.

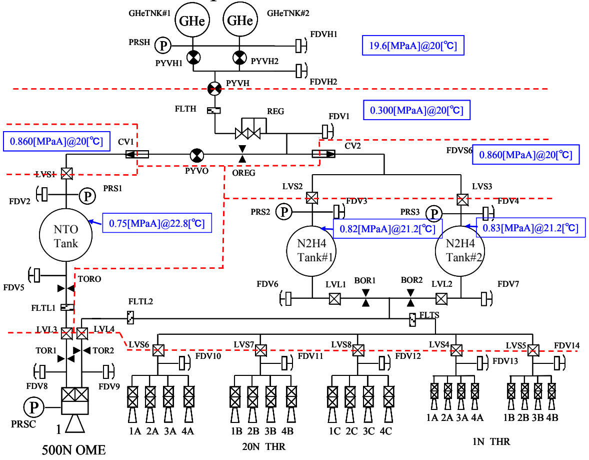


Figure 6 Pressure at Launch

3.2. Prime

After separation from the rocket the latch valves (LVS4, LVS5, LVS6, LVS7 and LVS8) of all thruster branches were opened. The valves' status changed from "CLOSE" to "OPEN" and the hydrazine tank pressure declined of slightly.

Shortly after priming the lines, a spin down maneuver was initiated to reduce the spin rate. This maneuver utilized 20N thrusters(A branch) and 1N(A branch) thrusters.

Before the ΔVc1, B branch and C branch thrusters were actuated for the check.

During the ΔVc1, NC pyrovalves downstream the pressurant tanks were opened normally

3.3. Maneuvers

Table 5 summarizes the maneuvers to the lunar observation orbit. Two types of maneuvers were used.

If it was necessary to obtain greater ΔV, the OME fired (OME maneuver). If not , the OME did not fire and 20N thrusters fired (20N thruster maneuver). Because the OME has more specific impulse (Isp) than the 20N thruster, an OME maneuver consuming less propellant. The 20N thruster has smaller impulse bit, a 20N thruster maneuver is advantageous for situations requiring precious control.

(1) OME Maneuvers(ΔVc1, ΔVp1, LOI-1, LOI-2, LOI-3, LOI-4 and LOI-5a)

Figure 6 depicts OME maneuver configuration.

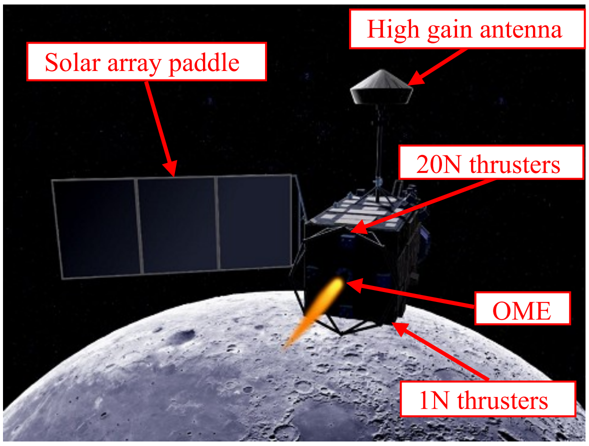


Figure 6 OME Maneuver Configuration

The steps of a OME maneuver are shown below.

1) The OME injector heater was switched on as the first step.
2) The propellant latch valves upstream the OME (LVL3 and LVL4) were opened.
3) The latch valves upstream the hydrazine tanks (LVS2 and LVS3) were opened. (for ΔVc1 only)
4) NC pyrovalve was opened for pressurant helium supply from pressurant tanks (for the first maneuver ΔVc1 only).
5) The latch valves upstream the MON-3 tank (LVS1) were opened.
6) At the beginning of a maneuver 20 N thrusters fired for propellants ullage settling.
7) OME started firing.
8) The OME injector heater was switched off automatically immediately after the OME firing start.
9) OME stop firing automatically at the planed ΔV.
10) The latch valve upstream the MON-3 tank was closed for prevention of MON-3 migration; the latch valves upstream the OME were closed for safety.

Figure 8 shows the pressure and estimated flow rate history of LOI-3 maneuver as typical data.

At the start firing 500N OME combustion chamber pressure rose to about 0.8[MPa] and tank pressure of hydrazine and MON-3 started declining slowly because tank pressure changed from regulator lockup pressure to regulated pressure. This pressure change corresponded to the propellants flow to OME. As the propellant tank pressure declined, the chamber pressure also declined. When the OME stop firing combustion chamber pressure decreased to 0.0[MPa] and tank pressure of propellants start rising slowly because tank pressure changed from regulated pressure to regulator lockup pressure. This change corresponded to the propellants stop. The pressure of helium pressurant started declining at about one min after the start OME firing and ceased declining at a few minutes after the OME stop.

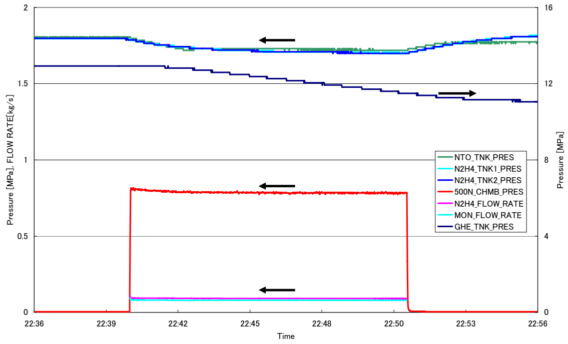


Figure 8 LOI-3 pressure history

Figure 9 shows the temperature history of LOI-3 maneuver.

Table 5 Maneuver Summary

Event	Orbit after maneuver			500N /20N	ΔV (m/s)	Firing time(s) *	Average Thrust (N)	Averag e Isp (s)	
	Center of Frame	Ra (km)	Rp (km)						
ΔVc1	earth	240000	6700	500N	23.18	158	553.6	319.8	Inserted orbit error correction
ΔVa1	earth	240000	7300	20N	0.56	37	—	—	Orbit control error correction
ΔVp1	earth	240000	7300	500N	93.34	524	553.2	319.8	Period adjustment
ΔVc2	earth	390000	7400	20N	1.12	57	—	—	Period error correction
ΔVp2	earth	380000	8600	20N	1.56	81	—	—	Period adjustment
LOI-1	moon	13000	1800	500N	298.80	1500	547.5	319.6	Lunar orbit insertion
LOI-2	moon	13000	1800	500N	102.48	509	554.9	319.6	Apolune altitude descent
LOI-3	moon	4100	1900	500N	151.44	710	552.5	319.5	Apolune altitude descent
LOI-4	moon	2500	1900	500N	164.96	696	554.3	319.6	Apolune altitude descent
LOI-5a	moon	2500	1900	500N	68.30	293	553.9	319.5	Apolune altitude descent
LOI-5b	moon	2100	1900	20N	25.73	1013	—	—	Apolune altitude descent
LOI-5c	moon	2000	1900	20N	25.30	983	—	—	Apolune altitude descent
LOI-6	moon	1900	1900	20N	12.82	497	—	—	Apolune altitude descent

* Firing time of 500N OME firing includes 40s ullage settling firing (by 20N thrusters)

At the OME start the OME injector temperature was an appropriate value about 50 [°C] which was achieved by the injector heater. The heater raised not only the injector temperature, but also that of the propellant valves slightly. After the start of OME firing the temperature of OME propellant valves declined because the propellants which flowed inside the valves cooled the warmer valves. During firing OME injector temperature became higher : about 200 [°C]. When firing stopped, the temperature of the injector and propellant valves rose to about 250 [°C] and 60 [°C] because of the heat soakback from the combustion chamber; it subsequently declined. All temperature were appropriate.

Figure 10 shows acceleration history of LOI-1 whose firing time was the longest of all the KAGUYA maneuvers. A smaller acceleration period at the beginning of the LOI-1 corresponds to ullage settling firing by 20N thrusters. After the settling higher acceleration generated by 500N OME firing, the initial part of the main acceleration was slightly greater because of slightly higher OME chamber pressure. The acceleration decreased corresponding to the OME chamber pressure. Subsequently, the acceleration gradually became higher which corresponded to KAGUYA mass decrease. The actual acceleration value agrees with the estimated acceleration from the thrust and the mass. The obtained ΔV and firing time indicate that the generated OME thrust was also nearly nominal.

OME total firing time was 4110s; total firing cycles were seven.

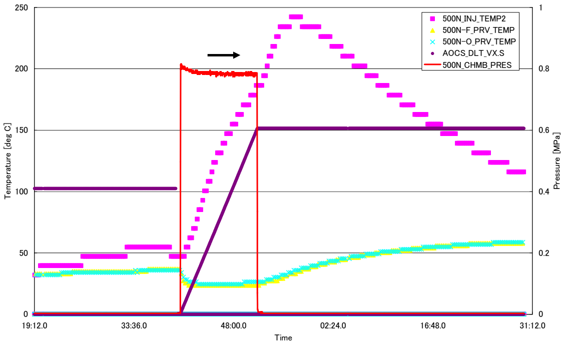


Figure 9 LOI-3 temperature history

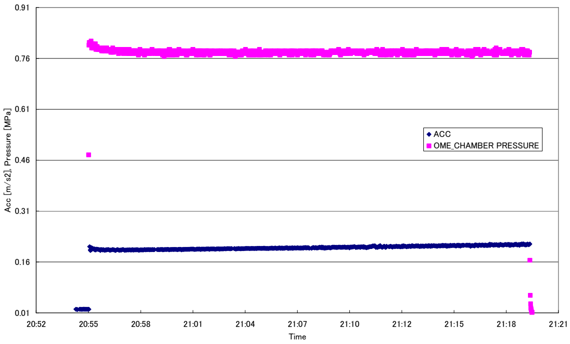


Figure 10 LOI-1 Acceleration history

(2) 20N thruster maneuvers(ΔVa1, ΔVc2, ΔVp2, LOI-5b, LOI-5c and LOI-6)

A simpler step of a 20N thruster maneuver than that of OME maneuver is described below.

1) The 20 N thrusters fired.
2) 20N thrusters stopped firing at the planed ΔV.

All 20N thruster maneuvers were performed normally.

4. Evaluation

Table 6 presents the temperature requirement for KAGUYA UPS. Despite various attitude during all the maneuvers, the UPS temperature remained within the required range.

Because the consumed propellant during the critical phase is estimated about 850kg, KAGUYA has sufficient hydrazine in constancy phase.

All tested components show that they are functional.

No in–space anomaly occurred in the KAGUYA UPS.

Table 6 Temperature Requirement

Component			Allowable Temperature Range
OME	Propellant Valve	Turn-on	5-60
		Active	5-120
		Inactive	5-120
	Injector Heater	Turn-on	5-150
		Active	5-370
		Inactive	-400
20N Thruster	Propellant valve		5-121
	Catbed		30-
1N Thruster	Propellant valve		5-121
	Catbed		200-
Helium Tank	Before OME Firing		0-40
Hydrazine Tank	Before OME Firing		15-25
MON-3 Tank	Before OME Firing		15-25

5. After maneuvers

After the final maneuver LOI-6 the Normally Open (NO) pyrovalves (PYVO and PYVH) upstream the MON-3 tank and regulator were closed to the prevent of MON-3 migration through the latch valve and check valve seal and to prevent helium leakage through the regulator.

Conclusion

The KAGUYA Propulsion System performed exceptionally well during the critical phase in-space operation: all functions, all temperatures and nearly nominal. Following a highly–accurate launch trajectory along with twelve successful ΔV and trajectory correction maneuvers, KAGUYA was inserted into lunar orbit on 18 October 2007, about 1 month after launch.

The authors thank the entire KAGUYA spacecraft and operations teams for their dedication. The combined efforts of the propulsion, spacecraft and operations members have supported the successful completion of 13 propulsive maneuvers.