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The Result of SELENE (KAGUYA) Development and Operation

Shin-ichi Sobue*[,1], Susumu Sasaki[1], Manabu Kato[1], Hironiri Maejima[1], Hiroyuki Minamino[1], Hisahiro Konishi[1], Hisashi Otake[1], Satoru Nakazawa[1], Naoki Tateno[1], Hirokazu Hoshino[1], Hayato Okumura[1], Katsuhide Yonekura[1], Yoshisada Takizawa[1], Kenji Ninomiya[1], Shuichi Matsumoto[1], Takahiro Iwata[1], Nobuhito Nomura[1], Michio Takahashi[1], Takeshi Sasaki[1], Yutaka Takano[1], Kai Matsui[1], Junichi Tanaka[1], Hiromi Ikeda[1], Mina Ogawa[1], Hitoshi Ikeda[1], Seiichi Sakamoto[1], Junichi Haruyama[1], Makiko Ohtake[1], Tsuneo Matsunaga[2], Hiroshi Araki[3], Hideo Hanada[3], Noriyuki Namiki[4], Junichi Yamazaki[5], Kazuhito Kasuga[6], Shingo Ikegami[6], Kazuhiro Abe[7], Kakuma Okazaki[7], Takayuki Sato[6], Wataru Masui[6], Aya Yamamoto[8], Takeo Fujita[8] and Akira Mukaida[8]

[1]*SELENE project, Japan Aerospace Exploration Agency, 2-1-1 Sengen, Tsukuba, Ibaraki 305-8505, Japan*

[2]*National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba-City, Ibaraki, 305-8506, Japan*

[3]*RISE project, National Astronomical Observatory of Japan, 2-12 Hoshigaoka-cho, Mizusawa, Iwate, 023-0861, Japan*

[4]*Planetary Exploration Research Center, Chiba Institute of Technology, 2-17-1 Tsudanuma, Narashino, Chiba 275-0016, Japan*

[5]*Science & Technical Research Laboratories, NHK, 2-2-1 Jinnan, Shibaya, Tokyo, 150-8001, Japan*

[6]*NEC Corporation, 1-10 Nishin-cho, Fuchu, Tokyo 183-8501, Japan*

[7]*Aerospace Department, NIPPI Corporation, 3175 Showa-machi, Kanazawa-ku, Japan*

[8]*Remote Sensing Technology Center of Japan, University, 106-0032, Roppongi, Japan*

Abstract: Japan's first large lunar explorer was launched by the H-IIA rocket on September 14, 2007 and had been in observation operation from December 21, 2007 to June 11, 2009(JST). This explorer named "KAGUYA (SELENE: SELenological and Engineering Explorer)" has been keenly anticipated by many countries as it represents the largest lunar exploration project of the post-Apollo program. The lunar missions that have been conducted so far have gathered a large amount of information on the Moon, but the mystery surrounding its origin and evolution remains unsolved. KAGUYA investigate d the entire moon in order to obtain information on its elemental and mineralogical distribution, its geography, its surface and subsurface structure, the remnants of its magnetic field and its gravity field using the scientific observation instruments. The results are expected to lead to a better overall understanding of the Moon's origin and evolution. Further, the environment around the Moon including plasma, the electromagnetic field and high-energy particles will also be observed. The data obtained in this way is of great scientific value and is also important information in the possibility of utilizing the Moon in the future. This paper describes the highlight of KAGUYA development and operation with some newly developed engineering achievements including a separation mechanism of sub-satellites from main orbiter as well as the latest scientific accomplishment of KAGUYA.

Keyword: SELENE, KAGUYA, H-IIA, JAXA, moon, origin and evolution, ground system, GIS, YouTube, WMS, EPO.

KAGUYA SATELLITE SYSTEM OVERVIEW

KAGUYA consists of a main orbiter at about 100km altitude and two sub-satellites (Relay Satellite named "OKINA" and VRAD Satellite named "OUNA") in lunar polar orbit. The main orbiter is also called as KAGUYA. The main orbiter weight at the launch is about 2.9 tons and the size of its main body is 2.1m×2.1m×4.8m. This satellite is 3 axis stabilized and the panel (+Z panel) on which mission instruments heads are installed is pointed to the gravity center of the Moon. About 3.5 kilo watt is the maximum power produced by a solar paddle. The surface of the KAGUYA is covered with the black color conductive MLI (multi-layer thermal insulators) for conductivity requirement of plasma observation instrument (PACE). The on-orbit configuration of the Main Orbiter is shown in Fig. (**1**) [1-3].

KAGUYA MISSION PROFILE

The Lunar transfer orbit which contributes to reduction of mission risk *via* two phasing loops around the Earth was adopted. KAGUYA was inserted into a polar elliptical orbit at a perilune altitude of 100 km of lunar. The two sub-

*Address correspondence to this author at the SELENE Project, Japan Aerospace Exploration Agency, Tsukuba, 305-8505, Japan;
E-mail: sobue.shinichi@jaxa.jp

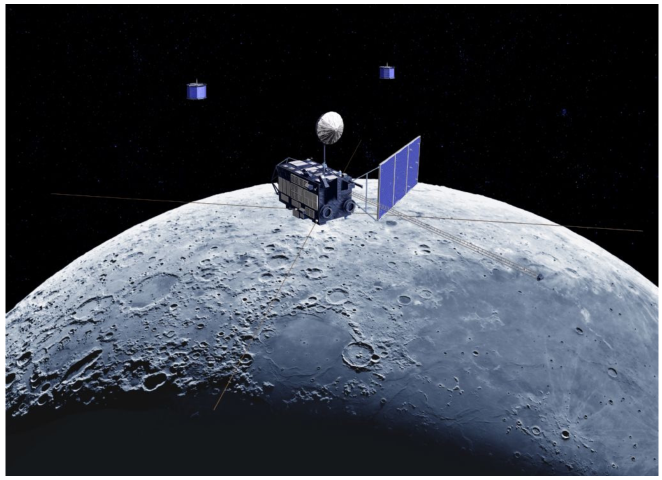

Fig. (1). The on-orbit configuration of the main orbiter.

satellites (OKINA and OUNA) were separated from the main orbiter at an apolune of 2,400 km and 800 km respectively. Finally the main orbiter reached the circular orbit at about 100 km altitude and the inclination of polar circular orbit is 90 deg. The apolune altitude of OKINA is determined to measure the gravity field anomaly on the far side of the Moon through relaying the Main orbiter s-band signal effectively. The apolune altitude of OUNA is selected for the low order gravity model coefficient measurements using radio sources on the OKINA and OUNA by VLBI method. When OKINA and OUNA separating from the main orbiter, the spin rotation power were added. This sub-satellite separation mechanism which gives the rotational and the translational force simultaneously was originally developed for JAXA's micro-lab satellite. To consider power generation, octagonal prism shape was selected for sub-satellites. All faces of satellite are covered with the solar cells, and each sell produces about 70 watt powers.

KAGUYA mission profile is shown in Fig. (**2**). OKINA was impacted to the far side of the Moon on February 11, 2009 and gravity anomaly observation at the far side of the Moon was successful completed.

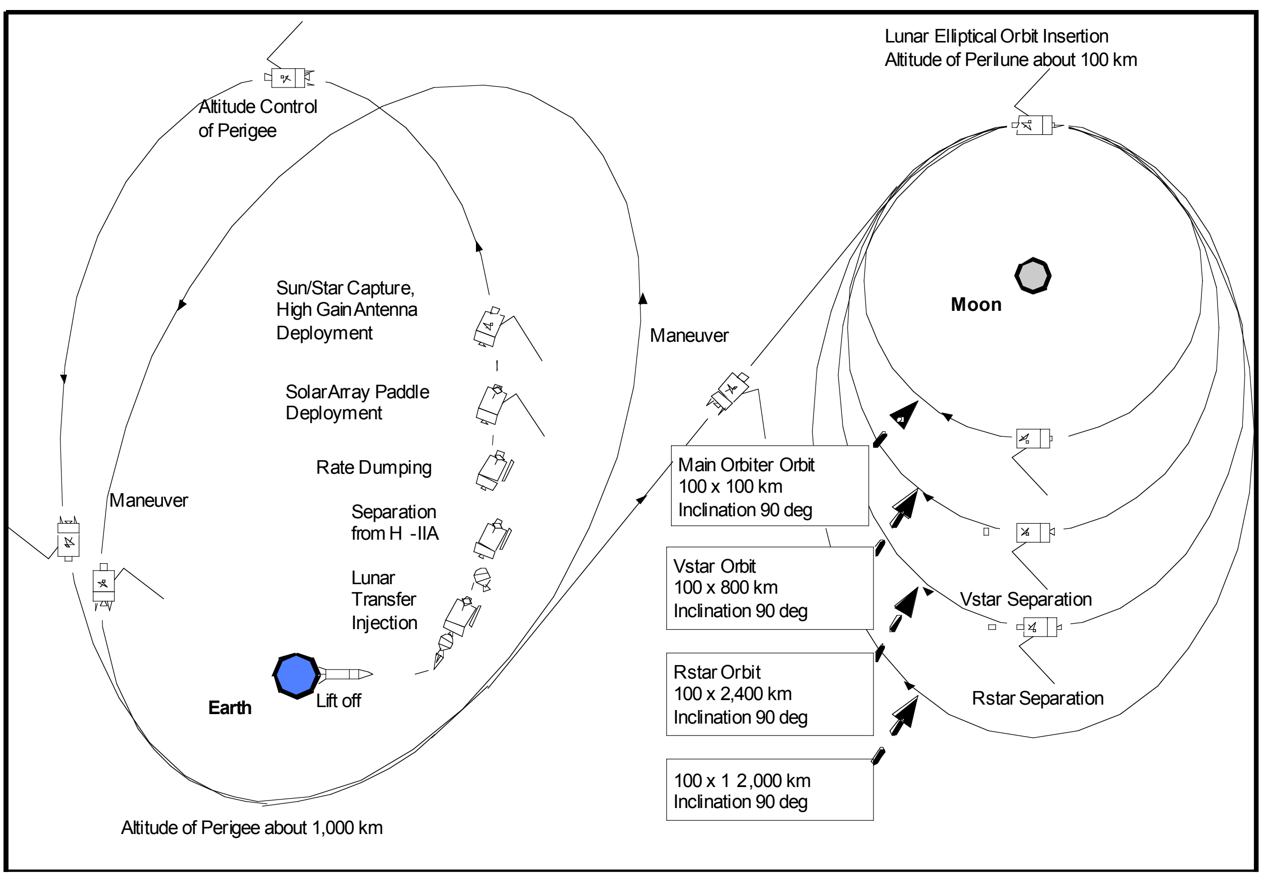

Fig. (2). KAGUYA mission profile.

Major events from lift off to the Moon for nominal observation, there were important events shown in Table **1** [4].

As the scheme for the trans-lunar trajectory, the phasing orbit method was selected considering the flexibilities for the contingencies during the initial operation and that much more launch trajectories are required for the direct transfer method. Five maneuvers adjusted the Kaguya orbit to encounter the moon at the altitude of 100km.Kaguya was injected to the lunar elliptical orbit on From the mission instruments requirements, the altitude of the main orbiter is specified as 100km±30km. The nominal mission observation period is about 10 months from finishing initial check out on December 21, 2007 to October 31, 2008.

On October, 2008, the nominal operation period of KAGUYA was successfully completed and the extended operation had been in operation until June 2009 when KAGUYA main orbiter impacted to the Moon. During the extended operation period, KAGUYA main orbiter descended from 100km - nominal observation orbit to 50km circular orbit on February 1, 2009 and on April 16, 2009 KAGUYA descended again to 10-30km as the lowest altitude (perilune) and 45-90km as apolune altitude. To have more precious observation result, especially, observation of magnetic field is much more precious for low altitude. Then, KAGUYA was impacted to the near side of the Moon at 3:25:10 a.m. on June 11, 2009 (JST) and the observation mission of KAGUYA was successful completed. Special extended operation outline of KAGUYA is shown in Table **2**.

During extended operation period, KAGUYA encountered a penumbral moon eclipse on 10 February 2009. We planned the view of the Sun from the KAGUYA almost covered by the Earth. We calculated the altitude of KAGUYA at capture timing. KAGUYA captured the moving image of the Earth and the Sun gradually rising from the Moon's surface by using HDTV camera. Fig. (**3**) is a cutout from the moving image to show the rising process. The image on the left is just after the Earth rise from the Moon's surface. It took about 47 seconds to film from the left to the right when the Sun came out from the Moon's surface and the diamond ring appeared. By using HDTV camera, KAGUYA provided full Earth-rise/Earth-set moving images with high vision quality. Its observation is the first time in the world and those images are used not only for the public outreach of the Moon but also for global environmental topic.

KAGUYA ENGIEERING ACHIEVEMENT

There is several engineering challenge to design and develop the Main orbiter satellite system to satisfy the tough engineering requirements to achieve various science mission instruments observation requirements. The one of the most critical technical challenge for KAGUYA is to develop separation system of sub-satellites (OKINA and OUNA) from the main orbiter. Because sub-satellite doesn't have the attitude control with the thruster and/or reaction wheel, it is very important to develop a reliable and rigid separation mechanism to provide necessary separation velocity and rotating spin speed. In addition, there is tough limitation of the mass of sub-satellites and it is also keen to develop new separation mechanism to reduce the mass. The outline of the separation system is shown in Fig. (**4**). The separation system consists of the separation brackets, separation spring and umbilical wire cutter and it is on an adapter plate of the main orbiter [5]. In general, a separation mechanism with turn table to provide rotation velocity is used for spin satellite but for OKINAand OUNA, a newly developed separation mechanism with two rings and extensible spring is applied. Two rings are twist and locked to provide rotation velocity before OKINA and OUNA separation. By the lashing's being liberated with the three explosive devices in the blankets, the extensible spring push the ring out to provide separation vector and the hook set up under a sub-satellite transfer the rotation velocity to an upper ring. To reduce weight mass of sub-satellite, the separation bracket is critical component and it holds the sub-satellites until separating the sub-satellite from the main orbiter at the Moon orbit. Three brackets are set 120 degrees each in the pitch direction on the circumference shown in Fig. (**4**). Each bracket consists of the lower bracket (side of the main orbiter) and the upper bracket (side of the sub-satellite) shown in Fig. (**5**). Until sub-satellite separation, lower bracket is coupled with upper bracket by a separation bolt and a separation nut. At the time of separation the separation bolt is released from the separation nut attached to the lower bracket. The separation direction is the tangential direction of the bracket circumference and the angle of separation is plus 10-degree.

An extensible spring named "Bow spring" is newly developed as light weight separation system and it is a separation initiator in Fig. (**6**) [6]. This spring consists of an upper ring, a lower ring, and longeron. The feature of this spring is to generate an axial direction velocity and a rotating one simultaneously without additional equipment as a separation actuator. In this case, a longeron is made from glass fiber and epoxy resin and it is used for reserving elastic potential energy by twisting the bow spring. The longeron is mounted a lower ring at the lower end, and it also mounted an upper ring at the upper end by the hinge pin. Since rotation angle of twisting the bow spring is about 8 degrees, the stored strain energy is about 5J. To reduce both a total mass and disturbance for separation, we adopted wire cutter to disconnect umbilical line, instead of a separation connector generally used. In this separation system, umbilical harness is cut by an ordnance wire cutter before separation. By using new this separation system, system mass is 4.37kg except for the adapter plate. The mass of a separation spring is 0.63kg. The design mass of the separation mechanism has been decreased to about 1/4 times less than normal separation system.

To confirm separation performance and separation stability, it is very important to verify it on the ground. It is also technical challenge to develop the performance of this separation mechanism with various microgravity conditions on the ground. Then, the device that imitated microgravity with rubber spring was designed by putting the separation mechanism on the position in which a dummy (mock) satellite was hung with elastic and the tension balanced gravity, shown in Fig. (**7**). It was a shock cord by which a small dummy satellite where mass characteristic is made to agree to the sub-satellite. Velocities and angular velocities are calculated on the basis of time series data of dummy satellite’s attitude and position. Vertical position and attitude are measured by three laser location sensors. Horizontal

Table 1. Major Events from Launch to Lunar Orbit Insert (LOI)

Events	Time (UTC)
Lift off	1:31:01, Sep 14, 2007
Satellite separation	2:33, Sep 14, 2007
SAP (Solar Array Paddle) deployment	2:43, Sep 14, 2007
HGA (High Gain Antenna) deployment	8:25, Sep 14, 2007
Vc1(delta V) by 500N thruster	20:12:58-20:14:56, Sep 14, 2007
Va1(delta V) by 20N thruster	22:59:44-23:00:21, Sep 15, 2007
Vp1(delta V) by 500N thruster	00:52:11-01:00:15, Sep 19, 2007
Va1(delta V) by 20N thruster	19:59:29-20:00:26, Sep 19, 2007
Va1(delta V) by 20N thruster	02:57:42-02:59:03, Sep 29, 2007
LOI1 (Lunar orbit injection) by 500N thruster	20:55:29-21:19:49, Oct 3, 2007
RSTAR (OKINA) separation	0:36, Oct 9, 2007
VSTAR (OUNA) separation	4:28, Oct 12, 2007
Final LOI by 20N	7:53:18-08:01:35, Oct 18, 2007

Table 2. Extended Operation Outline of KAGUYA

Period	Nov.2008-Jan.2009	Feb.2009-Apr.2009	Apr.2009-Jun.2009	Jun 11, 2009
Orbit	100km altitude	50km altitude	Low altitude perilune altitude :10~35km	----
Expected Result	Continuous observation	LMAG/PACE observation to observe three dimensional magnetic field of the Moon as primary. Other mission instruments will be in operation as much as possible		Demonstration of fundamental technologies such as orbit control

position and rotation about spin axis are measured by high speed video. In addition, at the ground test, re-useable separation nut simulator is used instead of the ordnance separation nut to release the separation bolt. Using a separation nut simulator contributes to reduction of cost and time. As well as ground test, this newly developed technology was demonstrated and verified by using JAXA's engineering testing small satellite named µLabSat. In addition, JAXA's HAYABUSA spacecraft is also carrying the similar separation spring(named helical spring) for its reentry capsule separation system.

The second critical technical challenge is to satisfy the requirement of electromagnetic compatibility (EMC), which has been performed through reducing magnetic interference and electromagnetic emissio [5-7]. In order to detect lunar weak magnetic anomaly field, all onboard electrical components were carefully designed and some had to be improved after initial EMC tests. In addition, Lunar Radar Sounder (LRS) on KAGUYA is to obtain subsurface structure to understand the tectonic and thermal history of the Moon by using radar sounding technology with two dipole antennas. LRS generates 4-6 MHz emission toward the lunar surface and detects its weak echo pulse by using high sensitive receivers. LRS, as a passive radar also observes the plasma waves around the Moon and the solar/planetary radio waves from 10 Hz to 30 MHz For this LRS observation mission, a more tough EMC requirement than the MIL standard had been applied to each onboard components, and therefore the radiated emission from the spacecraft had been expected to be sufficiently quiet. For coordinating the efficient development and the strict EMC conditions, it had been important to plan and execute systematic evaluation of each onboard component and to find practical solutions to compile the EMC performance. In order to minimize the magnetic field generated by the spacecraft, 1) Magnetic materials (Fe, Ni, SUS, Invar, etc.) should not be used, 2) If magnetic material is necessary, it should be demagnetized before integration, and should be controlled not to be magnetized and 3) The size of the current loop should be minimized, were strongly recommended to all devices. In fact, titanium bolts were used for integrating the spacecraft, and all wire lines were twisted. The current route of the battery-cell-unit was designed to minimize the effective current loop size, since a large current induces a strong magnetic field. The tools used for flight model integration were demagnetized before their use. Also possible magnetization of equipment in the test site and the launch point was carefully checked before the operations. On October 28, 2007 (during initial check out), the LMAG started the magnetic field measurement before extension of the mast. The magnetic field sensor attached on the tip of the 12 m mast moved away from the spacecraft with extension of the mast, and the magnetic field originated from various devices in the spacecraft was clearly decreased. Magnetic field data measured by LMAG in the lunar orbit were found not to be affected by the spacecraft operations.

Fig. (3). Sequence images of the Earth by the HDTV during the penumbral lunar eclipse.

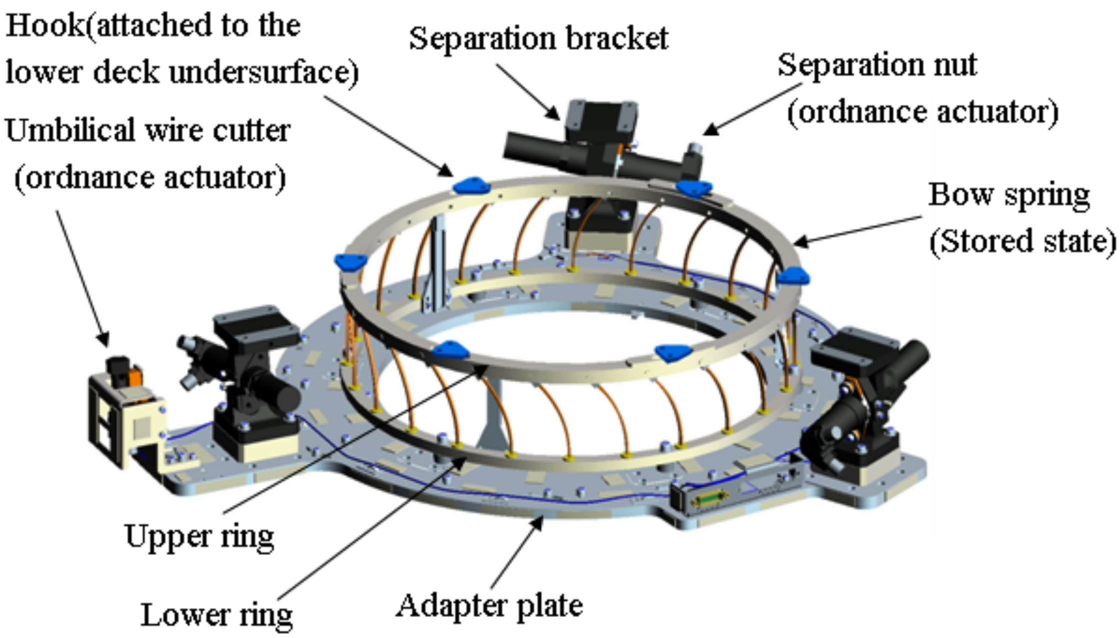

Fig. (4). Separation mechanism.

By separating the effect of the solar-terrestrial magnetic field from the data, the lunar magnetic anomaly was resolved. The two LRS dipole antennas were also deployed on October 29, 2007 and the initial checkout had been done. According to the initial check out data, the background noise level of LRS was as quiet as one confirmed in the final system EMC test before launch.

OPERATION SYSTEM

KAGUYA ground systems consist of (1) Tracking and Control system and (2) Mission Operation and Data Analyses system. Some of the "Tracking and Control System" and all of the "Mission Operation and Data Analyses system" are located at SELENE Operation and Analyses Center (SOAC) in JAXA Sagamihara campus. Fig. (**8**) shows the outline chart of "KAGUYA" Ground systems. KAGUYA Tracking and Control system consists of (1) Satellite control system, (2) Flight dynamics system, (3) Ground network, (4) Support information system and (5) Sagamihara campus institutional information system. JAXA Usuda Deep Space Center (UDSC) 64m, Uchinoura Space Center (USC) 34m and GN (Ground Network) 10m-class stations and NASA Deep Space Network (DSN) 34/26 m stations are used for the communication to "KAGUYA." All those stations are used for S-band TT&C (Tracking Telemetry and Command) communication of telemetry (40kbps normally and 2kbps in case of fewer line margin or directivity), command (1kbps) and tracking (Range and Range Rate (RARR)) operation. Omni antennas onboard were mainly used during the initial operation period. X-band mission telemetry data are transferred through High Gain Antenna (HGA) by 10Mbps and received at Usuda or Uchinoura. NASA DSN stations were used as a master station during the initial check out operation period and non-visible period from Japan at the eclipse of the Moon [8-10].

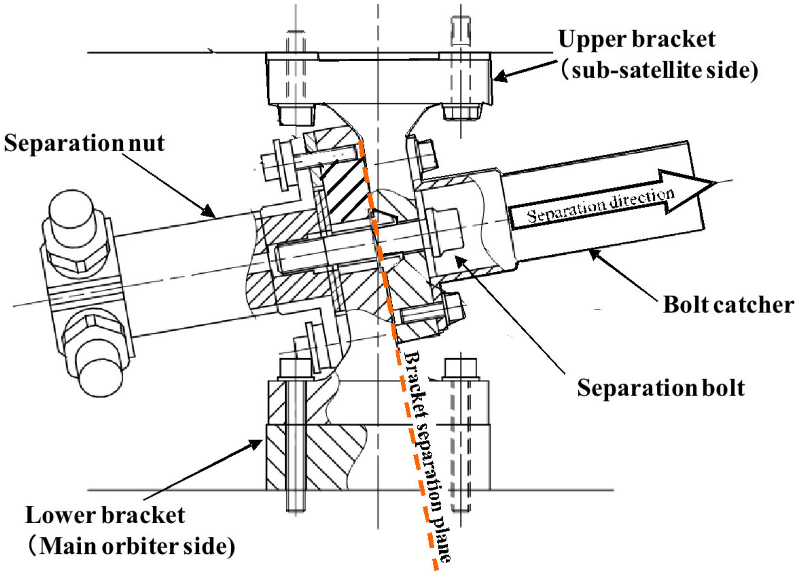

Fig. (5). Bracket mechanism.

All of the commands to the satellites are sent from SOAC and all the telemetry data received at each station are transmitted to SOAC. KAGUYA ground systems were developed and verified by the waterfall model through requirements analyses and specification, external / internal (detail) design, coding, software verification tests and operation tests by the End-to-End flow between the satellites and the end users of the ground systems. In the following, the outline of each system is described together with the development and operation results [11].

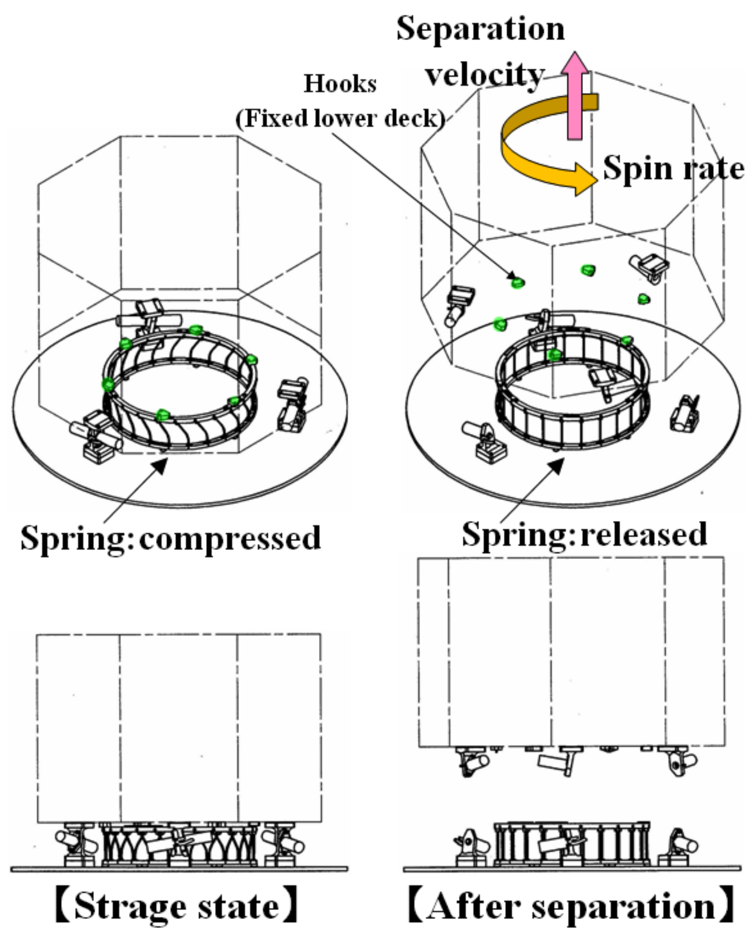

Fig. (6). Bow (extensible) spring and longeron.

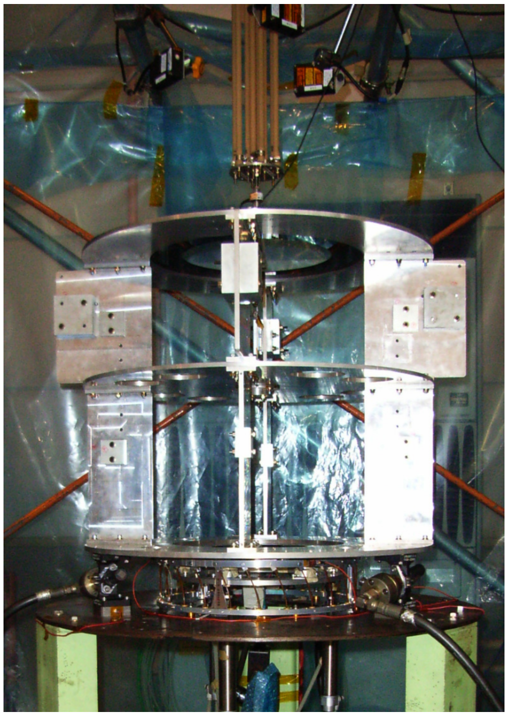

Fig. (7). Ground test configuration.

KAGUYA Mission Operation and Data Analyses systems consist of (1) Mission operation systems, (2) Level-0/1 processing system, (3) User terminal, (4) Level-2 (L2 data: KAGUYA standard products) Data Archive system, and (5) Image Galley and Web Map Service system. There are about 70 computers in Mission Operation and Data Analyses Systems and researchers of laboratories outside SOAC can access *via* Internet.

Level-0/1 processing system offers data for analyses to the researchers. Mission data are divided and processed from the raw telemetry data into CADU (CVCDU) by Virtual Channel Identifier (VCID) during Level-0 processing at first and into CCSDS packets by Application Process Identifier (APID) and calibrated data files converted from S-band House-Keeping (HK) telemetry data during Level-1 processing. Information files such as HK files for bus and mission instruments, satellite attitude and TI-UT relations etc. are also prepared. Orbital data are updated twice a week by Flight dynamics system and merged as data of one month in this system. Raw and calibrated telemetry data, information files (telemetry, command (plan and history), orbital and tracking data are archived and the amount of all Level-0/1 data reaches totally more than 20TB during the mission period.

L2 products can be archived up to about 50TB in L2 data archive system. By using KAGUYA L2 data archive system, users can search and download Level-2 processed data via Web browser. KAGUYA L2 data will be available for public users through the internet from November 1, 2009 (about 1 year after the end of KAGUYA nominal operation). L2 data will be archived and distributed in PDS-like format with the descriptions of data format and technical information. Before opening L2 data to public, KAGUYA image gallery and KAGUYA home page were opened and has been in operation to provide KAGUYA visualized images and

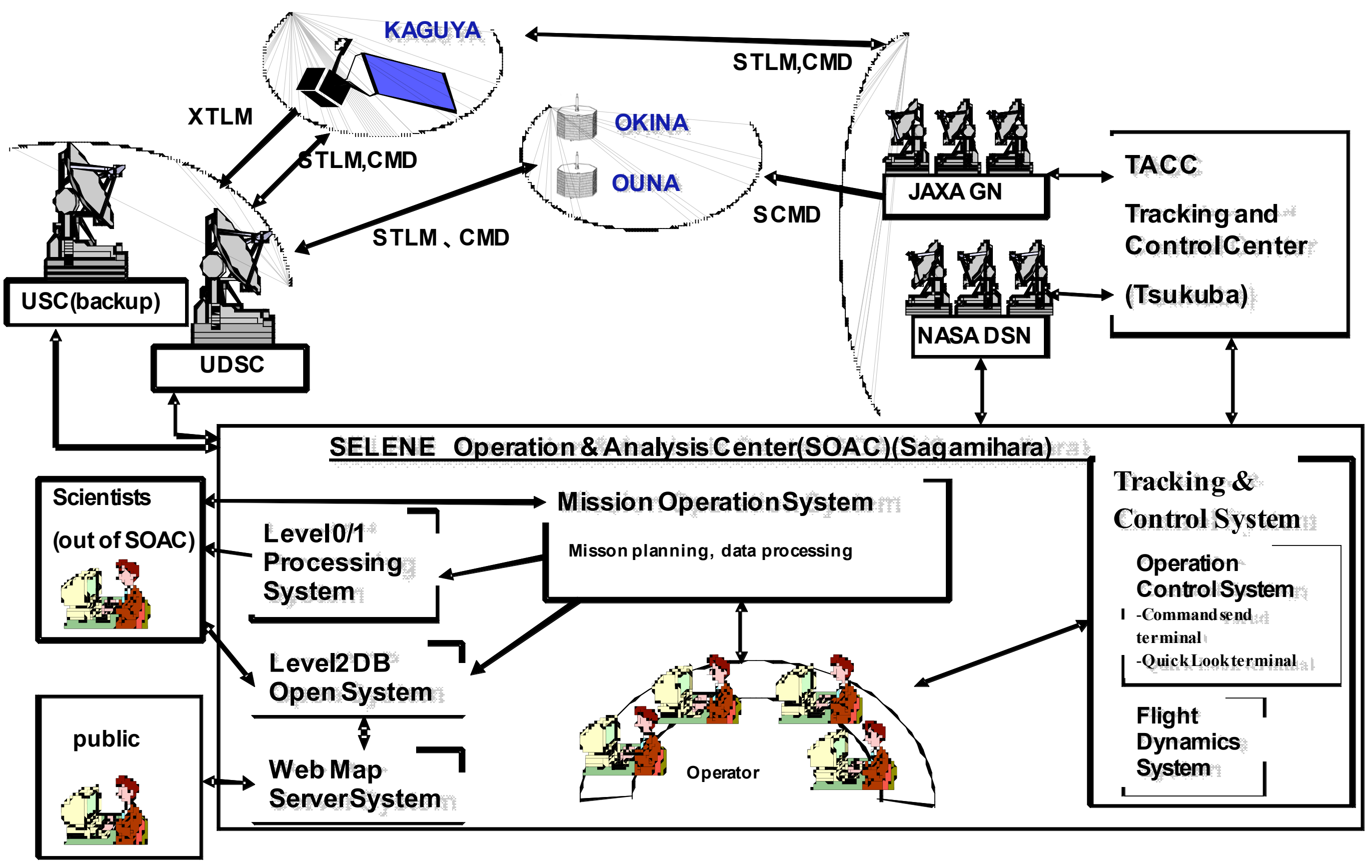

Fig. (8). KAGUYA operation systems.

movies with the latest KAGUYA news to promote KAGUYA (http://www.KAGUYA.jaxa.jp, http://wms.KAGUYA.jaxa.jp). In addition, KAGUYA movies by HDTV and TC are uploaded on JAXA channel in YouTube for KAGUYA promotion and public outreach (http://www.youtube.com/jaxachannel) [12, 13].

Since KAGUYA has 15 ongoing observation missions and obtains various physical quantity data of the moon such as elemental abundance, mineralogical composition, geological feature, magnetic field and gravity field, KAGUYA science team plans the integrated science using these various physical quantity data to obtain the new findings of origin and evolution of the moon. In the research of the integrated science, scientists have to access, compare and analyze much type of data with different resolution. Web-based GIS is considered to be the best way to progress such a study because it allows users to search, map, overlay, and share the data and information easily.

KAGUYA Web Map Server (WMS) which is adhering to OGC (Open GIS Consortium) standard has been implemented. KAGUYA WMS is located at JAXA Sagamihara Campus the same as L2DB. As of Dec. 2008, the following data are ingested to WMS and tested by internal KAGUYA scientists: global topographic map by Laser Altimeter(LALT), global gravity anomaly map by Relay Satellite(RSAT), global gamma-ray count rate map by Gamma-ray Spectrometer(GRS), coverage information of High-definition Television Camera (HDTV), etc.. This server will be open to the public on Nov. 2009. JAXA also selected NASA World Wind as a platform to browse the data from KAGUYA WMS. Users can easily map the various scientific data switching layers on the WW for KAGUYA and also display the observation area by polygon and icons which contain links to the original images and movies. In the future, we will try to display place-name using the WFS protocol and take the topographic data acquired by LALT as altitude parameter information for 3D display.

EARLY SCIENCE ACCOMPLISHMENT

There are 15 observation missions of "KAGUYA" and some initial results shown as below;

1) Chemical elements distribution - X-ray Spectrometer (XRS): the surface elemental composition (Al, Si, Mg, Fe, etc.) is determined through X-ray fluorescence spectrometry by irradiation of solar X-rays and Gamma Ray Spectrometer (GRS): the abundance of key elements (U, Th, K, H, etc.) is determined by measuring energy spectra of gamma-rays from the lunar surface with high energy resolution [14, 15].

2) Mineralogical distribution - Spectral Profiler(SP): the mineral composition of the Moon's surface is obtained by measuring the continuous visible and near infrared spectrum and Multi band Imager (MI): the mineral distribution is obtained by taking the visible and near infrared images of the Moon's surface in nine wavelength bands[15, 16].

3) Surface structure - Terrain Camera (TC): high-resolution geographical features are acquired by the stereo cameras, Laser Altimeter (LALT): to make the lunar topography model, the altitude is precisely measured using high-power laser pulses and Lunar Radar Sounder (LRS): the subsurface stratification and tectonic features in the shallow part of the lunar crust (a few km) by high-power RF pulses [17-19].

4) Surface and Space environment - Lunar Magnetometer (LMAG) :the magnetization structure on the Moon is acquired by measuring the lunar and the surrounding magnetic field, Plasma energy Angle and Composition Experiment (PACE): the three dimensional distribution of the low-energy electrons and mass-discriminated low-energy ions around the Moon are measured, Charged Particle Spectrometer (CPS): alpha rays from the Moon's surface and the

Table 3. 15 Observation Mission

	Observation	Instrument and Characteristics
Main Orbiter	Chemical elements distribution	X-ray Spectrometer (Al, Si, Mg, Fe distribution, spatial resolution 20 [km]) Gamma-ray Spectrometer (U, Th, K distribution, resolution 160 [km])
	Mineralogical distribution	Spectral Profiler (Continuous spectral profile λ= 0.5 to 2.6 [μm], spatial resolution 500 [m]) Multi-band Imager (UV-VIS-IR imager, λ= 0.4 to 1.6 [μm], 9 bands, spatial resolution 20 [m])
	Surface structure	Terrain Camera (High resolution stereo camera, spatial resolution 10 [m]) Lunar Radar Sounder (apparent depth 5 [km], resolution 100 [m]) Laser Altimeter (height resolution 5 [m], spatial resolution 1600 [m])
	Environment	Lunar Magnetometer (Magnetic field measurement, accuracy 0.5 [nT]) Plasma Imager (Observation of plasma sphere of the earth, XUV to VIS) Charged Particle Spectrometer (Measurement of high-energy particles) Plasma Analyzer (Charged particle energy and composition measurement)
	Public Outreach	High Definition Television camera (Images of the earth and the lunar surface, for public outreach)
VRAD satellite (OUNA)	Gravitational field distribution	VLBI Radio-source on the VRAD satellite (lunar gravitational field) (VRAD = VLBI RADio source)
	Environment	Radio Science (Detection of the tenuous lunar ionosphere)
Relay satellite (OKINA)	Gravitational field distribution	VLBI Radio-source on the Relay satellite (lunar gravitational field) Relay Sat. transponder (Far-side gravity field using 4-way range rate from ground station to Orbiter *via* Relay Satellite)

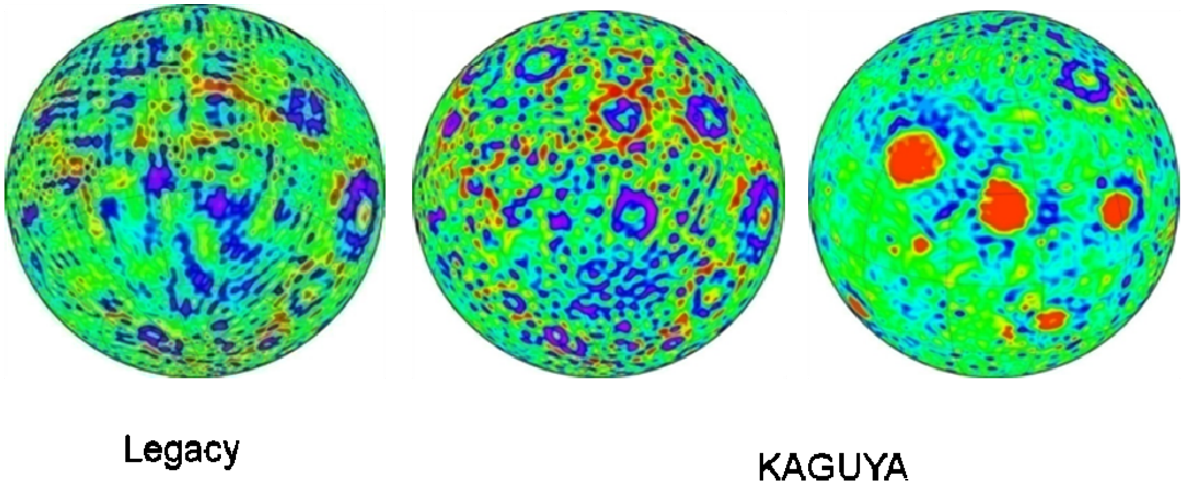

Fig. (9). Gravity Anomaly map (new far side map by using 4 Way Doppler and near side).

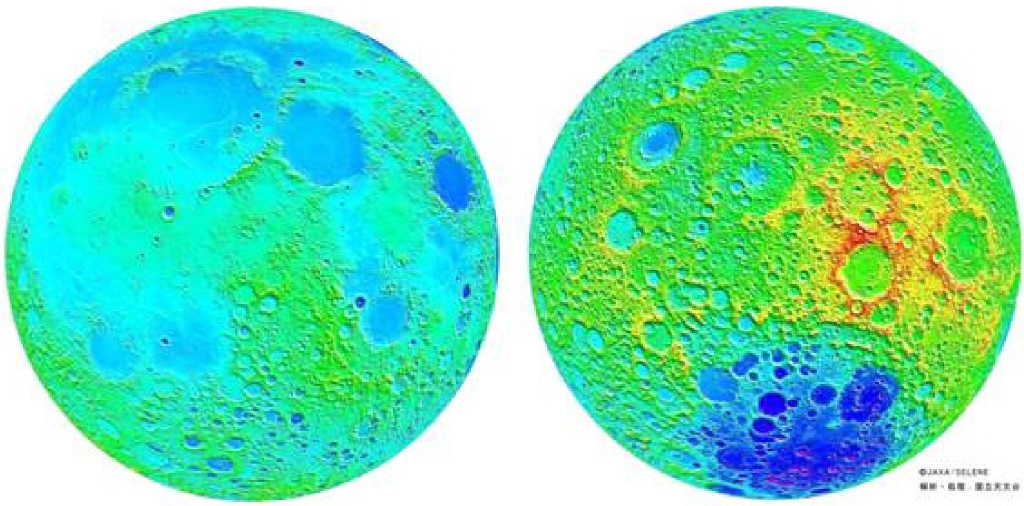

Fig. (10). LALT topographical map.

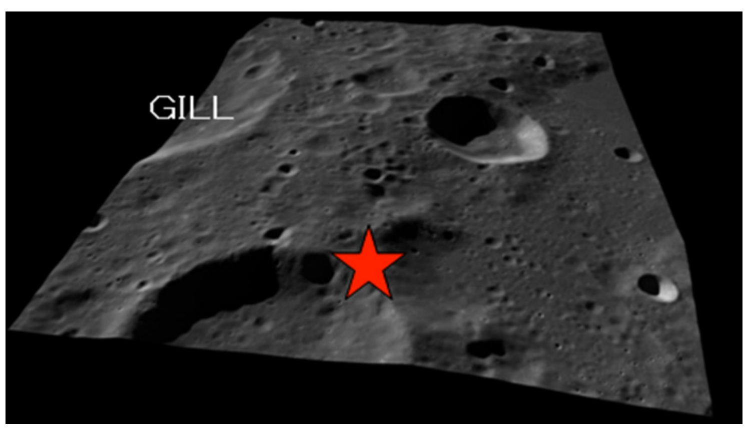

Fig. (11). Kaguya Impacted point 3D image by terrain camera (red star is impacted point of KAGUYA main orbiter).

abundance of cosmic ray particles are measured, Radio science [20, 21].

(RS): the Moon's ionosphere is detected by measuring the small deviation of the phase of RF signals from the VRAD satellite, and Upper-atmosphere and Plasma Imager (UPI): images of the magnetosphere and the ionosphere around the Earth are taken from the Moon to study the behavior of the plasma [22, 23].

5) Gravitational field distribution - Differential VLBI Radio Source (VRAD): the accurate gravity field data of the Moon are obtained by measuring the orbits of Relay and VRAD satellites using differential VLBI observation of S and X band radio waves and Four

way Doppler measurements by Relay satellite (OKINA) and Main Orbiter transponder (RSAT): the local gravity field of the far-side of the Moon is observed by measuring the disturbance of the orbit of the Main Orbiter using Doppler measurement [24, 25].

6) Public outreach - High Definition Television (HDTV): Taking pictures and movies of the Earth and the Moon with high-definition television cameras.

KAGUYA initial results have been publishing in international scientific society including Science, AGU GRL etc. Next, four papers s issued by Science on February 13th 2009 are shown as below.

1) Radar sounding from the KAGUYA spacecraft reveals subsurface layers at an apparent depth of several hundred meters in nearside Maria. Comparison with the surface geology in the Serenitatis basin implies that the prominent echoes are probably from buried regolith layers accumulated during the depositional hiatus of mare basalts. The basalts that accumulated during this quiet period have a total thickness of only a few hundred meters. These observations suggest that mascon loading did not produce the tectonics in Serenitatis after 3.55 Ga. Global cooling probably dominated the tectonics after 2.84 Ga [26].

2) The far side gravity field model of the Moon has been improved from the tracking data of the SELENE via a relay sub-satellite "Okina (Rstar)". The new gravity field (shown in Fig. **9**) model reveals that the far side impact basins have concentric rings of positive-negative-positive anomalies unlike plateau-shaped positive anomalies of the nearside basins, suggesting rigid lithosphere on the far side and compensation at the crust-mantle boundary on the near side. Far side basins are classified into two types depending on the magnitude of the central gravity high, indicating mantle uplift at a time of impact and association of mare volcanism with post-impact deformation. The basin structure possibly reflects the thermal state of the lithosphere, and gives an important clue to understand the thermal evolution of the Moon [27, 28] (shown in Fig. **10**).

3) A global lunar topographic map (shown in Fig. **10**) with a spatial resolution of finer than 0.5° has been derived using data from the laser altimeter (LALT) onboard the Japanese lunar explorer KAGUYA (SELENE). In a comparison with the previous Unified Lunar Control Network (ULCN 2005) model, the new map reveals unbiased lunar topography for scales finer than a few hundred kilometers. The newly derived lunar topographic spectrum indicates the lunar crust is rigid enough to support the surface topography that is rougher than that of the Earth, which may indicate the drier lithosphere of the Moon than the Earth. The highest point on the Moon is on the southern rim of the Dirichlet-Jackson basin and the lowest one is in the Antoniadi crater in the SPA. The topographic range is about 19.81 km, which is greater than the ULCN 2005 result that is 17.53 km for the next highest and lowest points whose positions are generally identical to our highest and lowest points with differences less than a few degrees [29].

4) The formation ages of geological units in mare can be determined by crater counting based on the idea as "a newly created surface will accumulate craters with time." The Terrain Camera aboard the KAGUYA provides high resolution (10 m / pixel) images to sufficiently detect small craters at 100km altitude. As a result of crater counting by TC observation data, several units at various locations including a part of the Mare Moscoviense on the lunar far side show their younger ages, clustering at -2.5 Ga, which were much younger than previously known on some far side mare units (-3.5 Ga). This result means "volcanic activity on the lunar far side lasted longer than previously considered and may have occurred episodically." "The long-lived far side volcanism" will be an important key factor for consideration on the lunar thermal evolution [30].

CONCLUSION

Although KAGUYA operation was successfully just finished on June 11, 2009 in near side of the Moon (shown in Fig. **11**), KAGUYA observation data was already started to show a better overall understanding of the Moon's origin and evolution. In addition, the environment around the Moon including plasma, the electromagnetic field and high-energy particles were also observed and provided new knowledge. The published papers also bring the usefulness of KAGUYA observation data in exploring the possibility of utilizing the Moon in the future. We expect more fruitful results from KAGUYA observation data in future. In addition, from November 2009 when KAGUYA L2 data will be open to public, KAGUYA observation data with other observational data by Clementine, Chandrayaan, Chang'e, LRO is expected to advance for lunar scientific research and future lunar utilization.

REFERENCES

[1] Sobue S, Sasaki S, Kato M, *et al*. Japan's Lunar Exploration Activity - Introduction of KAGUYA (SELENE). Asia-Pacific Satellite Communications Council 2008; 1.

[2] Takizawa Y, Sasaki S, Kato M. KAGUYA(SELENE) mission Overview, *Proceedings of the 26th International Symposium on Space Technology and Science (ISTS)* 2008 June 1-8: Hamamatsu, Japan 2008-k-20.

[3] Sasaki S, Kato M, Takizawa Y. KAGUYA(SELENE) Science Mission, *Proceedings of the 26th International Symposium on Space Technology and Science (ISTS)* 2008 June 1-8: Hamamatsu, Japan; 2008-K-21.

[4] Konishi H, Nomura N. The Operation result of SELENE (KAGUYA), *Proceedings of the 26th International Symposium on Space Technology and Science (ISTS)* 2008 June 1-8: Hamamatsu, Japan; 2008-K-26.

[5] Okazaki, K. JP11311282 (**1999**).

[6] Abe K, Okazaki K, Sato T, *et al.* Summary of the separation system for R/V-Star satellites of KAGUYA, Proceedings of *the 26th International Symposium on Space Technology and Science (ISTS)* 2008 June 1-8: Hamamatsu, Japan; 2008-K-37.

[7] Nakazawa S, Iiijma Y, Tsunakawa H, *et al.* Electromagnetic Compatibility of SELENE (KAGUYA), *Proceedings of the 26th International Symposium on Space Technology and Science (ISTS)* 2008 June 1-8: Hamamatsu, Japan; 2008-K-24.

[8] Shimizu H, Takahashi F, Horii N, *et al.* Ground calibration of the high-sensitivity SELENE lunar magnetometer LMAG. Earth Planets Space 2008; 60: 353-63.

[9] Kumamoto A, Ono T, Kasahara Y, *et al*. Electromagnetic compatibility (EMC) evaluation of the SELENE spacecraft for the lunar radar sounder (LRS) observations. Earth Planets Space 2008; 60: 333-40.

[10] Matsumoto S, Takizawa Y, Ogawa M, *et al.* Flight trajectory and control system of selenological engineer explore KAGUYA" mission to the Moon, *Proceedings of the AIAA Guidance, Navigation, and Control Conference* 2008: Honolulu, Hawaii; AIAA-2008-7483.

[11] Matsumoto S, Takizawa Y, Konishi H, *et al.* Lunar transfer orbit for SELENE, *Proceedings of the 25th International Symposium on Space Technology and Science and the 19th International Symposium on Space Flight Dynamics* 2006: Kanazawa, Japan, ISTS 2006-d-31.

[12] Kawakatsu Y, Nakajima K, Ogasawara K, *et al*. KAGUYA translunar trajectory and lunar orbit injection, *Proceedings of the 14th International Symposium on Space Flight Dynamics* 1999: Brazil.

[13] Hoshino H, Yonekura K, Ogawa M, *et al.* Operation results of "KAGUYA(SELENE)" ground systems, *Proceedings of the 27th International Symposium on Space Technology and Science (ISTS)* 2009 June 6- 12: Tsukuba, Japan; 2009-o-3-03v

[14] Okumura H, Sobue S, Hoshino H, *et al.* Data archive and visualization for lunar orbiter KAGUYA (SELENE); Proceedings of 40th Lunar and Planetary Science Conference; 2009: Woodlands, Texas, USA.

[15] Sobue S, Kato M, Hoshino H, *et al.* KAGUYA(SELENE) data delivery and EPO plan, *Proceedings of the 26th International Symposium on Space Technology and Science (ISTS)* 2008 June 1-8: Hamamatsu, Japan; 2008-K-25.

[16] Okada T, Kato M, Yamashita Y, *et al.* Lunar X-ray spectrometer experiment on the SELENE mission. Adv Space Res 2002; 30:1909-14.

[17] Hasebe N, Shibamura E, Miyachi, *et al*. High Performance Germanium Gamma-Ray Spectrometer On Lunar Polar Orbiter SELENE (KAGUYA), *Proceedings of the 26th International Symposium on Space Technology and Science (ISTS)* 2008 June 1-8: Hamamatsu, Japan; 2008-k-41.

[18] Ohtake M, Haruyama J, Matsunaga T, *et al.* The multi bandimager for the selene mission, *Proceedings of the 23rd International Symposium on Space Technology and Science (ISTS)* 2002: Matsue, Japan; 2002-k-27.

[19] Matsunaga T, Ohtake M, Hirahara Y, *et al.* Development of a visible and near infrared spectrometer for Selenological and Engineering Explorer (SELENE); *Proceedings of SPIE* 2000: San Diego, CA, USA; Vol. 4151, pp. 32-39.

[20] Haruyama J, Matsunaga T, Ohtake M, *et al.* Global lunar-surface mapping experiment by the lunar imager/spectrometer on SELENE. Earth Planets Space 2008; 60: 243-56.

[21] Tsubokawa T, Araki H, Tazawa S, *et al.* Development of laser altimeter (LALT) on board SELENE orbiter, *Proceedings of the 23rd International Symposium on Space Technology and Science (ISTS)* 2002: Matsue, Japan; 2002-k-25.

[22] Ono T, Oya H. Lunar radar sounder (LRS) experiment on-board the SELENE spacecraft. Earth Planets Space 2000; 5: 629-37.

[23] Saito Y, Yokota S, Asamura K, *et al.* Low energy charged particle measurement by MAP-PACE onboard SELENE. Earth Planets Space 2008; 4: 375-86.

[24] Yoshikawa I, Yamazaki A, Murakami G, *et al*. Telescope of extreme ultraviolet (TEX) onboard SELENE:science from the Moon. Earth Planets Space 2008; 60: 407-16.

[25] Imamura T, Oyama K, Iwata T, *et al.* Studying the lunar ionosphere with the SELENE radio science experiment, *Proceedings of the 26th International Symposium on Space Technology and Science (ISTS)* 2008 June 1-8: Hamamatsu, Japan; 2008-k-54.

[26] Ono T, Kumamoto A, Nakagawa H, *et al.* Lunar radar sounder observations of subsurface layers under the nearside maria of the moon. Science 2009; 323: 909-12.

[27] Namiki N, Hanada H, Tsubokawa T, *et al.* RSAT/VRAD/LALT mission groups. Selenodetic experiments of SELENE: Relay subsatellite, differential VLBI, and laser altimeter. Adv Space Res 1999; 23: 1817-20.

[28] Namiki N, Iwata T, Matsumoto K, *et al.* Farside gravity field of the moon from four-way doppler measurements of SELENE (KAGUYA). Science 2009; 323: 900-5.

[29] Araki H, Tazawa S, Noda H, *et al.* Lunar Global shape and polar topography derived from KAGUYA-LALT laser altimetry. Science 2009; 323: 897-900.

[30] Haruyama J, Ohtake M, Matsunaga T, *et al.* Long-lived volcanism on the lunar farside revealed by SELENE terrain camera. Science 2009; 323: 905-08.

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