High Performance Germanium Gamma-Ray Spectrometer On Lunar Polar Orbiter SELENE (KAGUYA)

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The high precision gamma-ray spectrometer (GRS) is carried on the first Japan’s large-scaled lunar explorer, SELENE (KAGUYA), successfully launched by the H-IIA rocket on Sep. 14, 2007. The GRS consists of a large Ge crystal as a main detector and massive bismuth germanate crystals and a plastic scintillator as anticoincidence detectors. The Ge detector is cooled and kept below 90K by a Stirling cryocooler. After a series of initial health check of the GRS, it started a regular observation on December 21, 2007. Energy spectra of gamma rays are obtained with a good energy resolution over the lunar surface. Energy spectra including many peaks of major elements and trace elements on the lunar surface have been measured by the GRS. The GRS identified individual gamma-ray lines emitted from the lunar surface and provided the global intensity maps of naturally radioactive elements. Here, we review an in-flight performance of the GRS and the initial results observed during the period from Dec. 21, 2007 to Feb. 17, 2008.

Key Words: Moon, KAGUYA, Chemical Composition, Gamma

1. Introduction

Determining the distribution of major and important trace elements on the lunar surface is essential in the lunar science. Those elements provide clues to the conditions during the formation of the Moon. Planetological studies combined with elemental study can help improve our understanding of the evolution of the terrestrial planets including the Earth. Gamma-ray spectroscopy is suited for measuring elemental composition on the lunar surface.

The gamma rays measured from the Moon can be used to infer the composition of the top few centimeters of the surface. Some gamma rays are made by the decay of naturally radioactive elements, K, Th and U. Many gamma rays are made by fast and thermal neutrons produced by cosmic ray particles. Energies of gamma rays identify nuclides from which they were emitted and their fluxes are closely related to the elemental concentration.

Planetary missions carrying gamma-ray spectrometers (GRS) so far have proved them to be a powerful tool which provides precious information on the chemical abundance of the surface of planetary bodies. However, previous lunar missions, Apollo1) and Lunar Prospector2), have conducted gamma-ray measurements by detectors with limited energy resolutions. Energy resolution severely affects the scientific outcome and its quality achieved by gamma-ray measurements is often very hard to identify individual chemical elements. In SELENE (KAGUYA), therefore, a Ge detector is adopted as a main detector of its GRS because of its excellent energy resolution, which is the first one to use a Ge detector for a lunar mission3). The GRS will provide precise global abundance of those elements on the lunar surface by remote sensing and also provide the precious data for the future utilization of lunar resources.
The Japanese lunar mission SELENE consists of a main orbiter KAGUYA and two small daughter satellites (Relay Satellite and VRAD Satellite), successfully launched from Tanegashima Space Center on Sep. 14, 2007\textsuperscript{31}. The main orbiter carries a gamma-ray spectrometer with a large germanium semiconductor detector as a main detector and bismuth germanate and plastic scintillators as an active shielding\textsuperscript{29}. With the highest energy resolution, the GRS provides the concentrations of the major elements and natural radioactive elements of the material of the lunar surface. Here, the initial results of the GRS obtained during the period from Dec. 21, 2007 to Feb. 17, 2008 are shown and discussed.

2. Instrumentation

2.1. Gamma-ray spectrometer

The GRS onboard the SELENE (KAGUYA) observes lunar gamma rays to obtain chemical abundance with high precision over the entire lunar surface. In order to carry out such a gamma-ray spectroscopy, we have designed and developed a flight model of the GRS. The GRS consists of three subsystems, Gamma-ray Detector (GRD), Cooler Driving Unit (CDU) and Gamma-ray and Particle detectors Electronics (GPE). The GRD subsystem looking at the nadir is placed on the lunar side of the spacecraft, and the others are installed inside the spacecraft. The CDU controlled by the GPE subsystem drives a cryocooler to cool a large Ge semiconductor crystal below 90K. The GPE contains analog and digital boards for data processing and analyzing, and CPU boards for data handling, transmitting and command analysis. The detail of the GRS is described in the paper\textsuperscript{30}. The GRD subsystem consists of a set of radiation detectors, preamplifiers, high voltage supplies and their filters, Stirling cryocooler and thermal radiator (see Fig. 1). Stirling cryocooler and thermal radiator are shown in Fig. 1. The detectors include a high purity n-type Ge crystal, and a massive bismuth germanate oxide Bi\textsubscript{4}Ge\textsubscript{3}O\textsubscript{12} scintillator shield, and a plastic scintillator. Those scintillators work as anticoincidence detectors to reduce background gamma rays.

![Fig. 1. Schematic drawing of the Gamma-Ray Spectrometer (GRS) on SELENE (KAGUYA). It consists of a large Ge detector as a main detector cooled with a Stirling cooler and BGO and plastic scintillators as an anticoincidence counter.](image)

The Ge detector has an n-type, coaxial cylindrical germanium crystal with a volume of 252 cm\textsuperscript{3}. The Ge crystal is cooled by a Stirling cryocooler. A vibration-reduced cryocooler system based on the Stirling cooler was developed for SELENE GRS. In this system, microphonic noise due to the vibration of cryocooler system was confirmed to be smaller than other noises caused by electronics circuits and the Ge detector itself.

In order to increase the sensitivity of a GRS, it is essential to reduce background gamma rays. The major background components are cosmic-ray particles entering the detectors, produced particles due to the primary and secondary cosmic-ray interactions with materials of spacecraft, and scattered gamma rays produced in planetary surfaces and in detector materials themselves. For the reduction of those backgrounds, SELENE GRS employed BGO and plastic scintillators as an active shield. The Ge detector is surrounded by a horseshoe-shaped BGO detector. The thickness of a part facing the spacecraft is so thick that background gamma rays from the spacecraft can be greatly reduced, while its lunar side is not covered by BGO detector, instead of which a 5mm plastic scintillator is placed to reduce albedo charged particles, through which gamma rays can pass without energy loss due to its low density. The BGO shield also reduces Compton backgrounds by an anti-coincedence operation.

2.2. Spatial response function of SELENE GRS

A spatial response function (SRF) is of importance for a gamma-ray remote sensing because it determines the effective area that GRS views the Moon, i.e. the spatial resolution. In addition, it converts counting rates of gamma rays at the orbit, \( C_{rate} \), to fluxes on the lunar surface. Thus, the SRF is used to deduce the absolute abundance of lunar elements.

The relationship between \( C_{rate} \) and the surface flux is

\[
C_{rate} = \int \int f_{int}(\theta_1, \varphi_1) \cdot \omega(\theta_1, \varphi_1) \cdot f(\theta_1, \varphi_1) \cdot dS, \quad (1)
\]

where \( \theta_1 \) and \( \varphi_1 \) are the latitude and longitude of a position on the lunar surface, respectively. \( \omega_{int} \) and \( \omega \) are the photo-peak efficiency to a gamma ray from the position \( (\theta_1, \varphi_1) \) and the solid angle subtended by the Ge crystal viewed. \( f \) is the differential flux at the lunar surface of gamma rays which directs to the Ge crystal. The SRF, \( \Pi(\theta_1, \varphi_1) \), is defined as

\[
\Pi(\theta_1, \varphi_1) = \frac{1}{C_{rate}} \cdot f_{int}(\theta_1, \varphi_1) \cdot \omega(\theta_1, \varphi_1) \cdot f(\theta_1, \varphi_1), \quad (2)
\]

and it is proportional to the probability to detect a gamma ray produced at the position \( (\theta_1, \varphi_1) \) on the lunar surface.

The calculation of the SRF was difficult because the detection efficiencies to gamma rays with any incident directions should be known. It was not realistic so far to calculate the detection efficiency for a complicated shape of a gamma-ray spectrometer, such as the GRS.

Thus, a Monte Carlo simulation code to calculate transportation of particles, Geant4 code, was used to deduce the detection efficiency and the SRF of the GRS. Some preliminary results of the SRF are shown in the paper\textsuperscript{31} where...
the Ge crystal, BGO and plastic scintillators are only taken into account. Recently, the detailed modeling of the GRS has been finished by Geant4. In this model, the aluminum case of GRD, photo multiplier tubes and cooling devices are included and the model is shown in Fig.2. The model is checked by comparison of photo peak efficiencies between the experimental result at ground tests and the simulation results. We found that the accuracy of the model is within ±20%.

The SRF of the GRS was calculated on the basis of the model by using Geant4\(^4\). The solid angle and the detection efficiency were obtained for 6841 incident directions. The calculation of SRFs from 0.2 to 10 MeV has been finished and the database of SRF has been constructed. The SRF of the GRS for 1.5 MeV is shown in Fig.3. The full width of half maximum of the SRF, spatial resolution, is 130 - 134 km for 1.5 MeV at 100 km altitude, which slightly depends on the direction of gamma ray, but almost isotropic. The anisotropy of SRF is found for low energy gamma rays, because of shielding effects. For instance, the spatial resolution varies between 105 and 130 km for 0.2 MeV.

Fig. 2. The model of GRS on SELENE (KAGUYA) to calculate the response function by Geant4.

Fig. 3. Normalized spatial response function of the GRS on SELENE (KAGUYA) for 1.5 MeV gamma rays. The maximum of the function is normalized to 100.

3. Observation

3.1. In-flight operation of GRS

SELENE was injected into the lunar orbit on Oct. 4, 2007, via its phasing orbit to the Moon. After injection into circular orbit at 100 km altitude of approximately two hours periodicity, a series of health and function checks were made for the GRS as well as the other scientific instruments.

Before checking various functions of GRS system, cooling system switched on and a driving voltage of the cooler was increased step-by-step to cool the Ge detector to 90K or below. And all the electronic functions for Ge and scintillators were checked without applying high voltage to those detectors. Then BGO and plastic scintillators were operated by applying high voltages from 0 to 1.1 kV by stepping up 6 V to photo-tubes. Ge detector system is checked by applying high voltage little by little when anti-coincident system was not operated. Finally, the anti-coincident operation was checked for the GRS system and all the function tests showed fine by means of evidence that GRS systems worked well for the measurement of lunar gamma rays.

The mission operation was shifted to its regular observation on Dec. 21, 2007. In the regular observation mode, the high voltage of 3.1 kV was applied to a Ge detector. The light outputs from a BGO scintillator and a plastic scintillator are read out by PMT, and those signals from the scintillators are used as the anti-coincidence signals against the Ge signals. The Ge detector is cooled below 90 K in lunar orbit and the temperature was eventually achieved to be 75 K with the driving voltage of 14V as expected. From a viewpoint of the stability of pulse height from Ge detector, the temperatures of those detectors and their electronics are preferred to be stable. Sensor subsystem GRD looking at the nadir of the Moon, however, is susceptible to periodic heat input from lunar albedo. HK data of the GRS in the regular operation after the checkout one showed the quite stable state in the temperature of the sensor subsystem.

While the beta angle changes, the heat input from the Moon varies during a periodic motion in orbit. At β = 90 deg, the spacecraft environment of SELENE becomes so low in temperature that the driving voltage for the cryocooler was lowered to 13 V and the Ge detector was kept to be 75 K. The driving voltage only was changed little by little in response to the beta angle.

SELENE GRS has been observing the lunar surface under very stable conditions from the beginning of the observation to the end of February so far. The time series variations of counting rate of the Ge detector and its temperature are shown in Fig. 4(a). The counting rate varies mostly depending on the altitude of the satellite. It is attributed to the fact that the horse-shoe-shaped BGO shielding limits the field of view of the GRS, even though the main Ge detector itself is omni-directional. The Ge crystal is kept cold below 80 K during observation, and the temperatures are also very stable, which minimizes the gain drift and the effect of radiation damage. If the detector is once warmed above temperature and then cooled to operation temperatures, the damage is prominently observed in the energy spectrum.

When the beta angle changes from β = 0 to 90 deg, the
temperature of the baseplate of the GRD varied from 0 to 8 °C ±2 °C, while the temperature of the Ge, 75 to 80 K±0.5 K. The Ge detector is mostly kept to be constant within the precision of ±0.5 °C during a period of SELENE orbit (about 2 hours). In spite of the periodic heat input, the temperature of baseplate of GRD was well controlled by a heater to be about 0 deg C or less, within a precision of ±2 °C. The temperature variation monitored for GRD subsystem in the GRS are shown in Fig.4(a).

The counting rates/17sec of Ge detector are shown in the energy range of 100 keV – 12 MeV (bottom) and >12 MeV (top) in Fig. 4(b). The variation of counting rate is 20% or less. The variation during an orbital period is mainly caused by the difference of emission rate of gamma-rays depending on the elemental abundance. The counting rate over the Procellarum KREEP Terrain is the highest, while the far side terrain in the northern hemisphere is the lowest as discussed later. No peaks of line gamma-rays but continuous gamma-rays can be seen in the energy spectrum over 8 MeV (see Fig.5). Those gamma-rays are produced from pai-zero decay through the nuclear interaction of lunar material with cosmic rays. The reason why the counting rate over 12 MeV is more than that in the range 0.1 - 12 MeV as can be seen in Fig. 4(b) is caused by high energy gamma-rays produced from pai-zero decay. Therefore, the counting rates over 8 MeV and over 12 MeV become a measure for the variation of GCR intensity and solar activity related to the solar particle events.

The Ge detector of the GRS has been constantly exposed to galactic cosmic rays since the launch date of September 17. After the regular observation, the detector had been for about 3 months. During this period, the solar activity was at solar cycle minimum and so quiet that no solar proton events were observed. However, the intensity of galactic cosmic rays was at maximum and about 1 protons/cm² were exposed to the detectors for 3 months. Fig.4(c) shows an energy resolution of the 40K peak at 1.461 MeV measured by the GRS as a function of exposure days. In the ground test, the resolution was about 3.0 keV. Most of peaks in-flight data have a low energy long-tail, while the shape of the upper half has almost a Gaussian shape. The photopeak distribution of gamma-ray lines becomes wider with the lapse of time in space and the accumulation of exposure time, especially after the large increase in temperature of the Ge crystal on Nov. 16, Jan. 2, and Feb. 4 because of satellite operations. Considering the above phenomena, the degradation of energy resolutions is most likely caused by the radiation damage of the Ge crystal. However, SELENE GRS still retains an energy resolution 10 times better than other past and present missions by scintillators. To recover its finest energy resolutions, annealing plans are under consideration.

In-flight observation, anti-coincidence system was always operated. When a high energy charged particle or a Compton scattered gamma-ray simultaneously hits and produces the signals in the main-detector and anti-coincidence detector, the Ge detector signal is canceled in the anti-coincidence operation. Energy spectra of gamma rays with the energies from 100 keV to 12 MeV obtained by the GRS with or without operation of anti-coincidence system are shown in Fig. 5. Top spectrum is obtained with no operation of anti-coincidence, though background gamma rays, especially from spacecraft body, are absorbed by massive shield with thick BGO scintillator and coincident events of charged particles are vetoed. Bottom spectrum was obtained by the anti-coincidence operation system. From the comparison of these spectra, a remarkable reduction of gamma-ray continuum, was made by the anti-coincident operation due to Compton suppression system. Many peaks of gamma-ray lines can be seen in the anti-coincident spectrum of gamma rays, while the top spectrum does not have peaks except for intense lines of gamma rays. The level of background continuum in the energy range over 2 MeV is decreased by a factor of 5 to 20. It is found that the anti-coincidence operation is very effective for the background reduction.
Fig. 4. (a) Time variations of temperatures at Ge detector, baseplate of GRD, (b) time variations of gamma-ray counts in the energy interval of 0–12 MeV (A), and over 12 MeV (B), and (c) energy resolution of the Ge detector used in the GRS.

The energy spectra include not only gamma rays induced

Fig. 5. Comparison of energy spectra of gamma rays obtained with and without the anti-coincidence operation. Compton continuum of the spectrum, especially in the higher energy region, is found to be greatly reduced by the active shielding.

3.2. Initial observation

Gamma rays emitted from the lunar surface were measured by GRS on the SELENE (KAGUYA) at around 100 km in altitude. GRS provides energy spectra of gamma rays with two different energy ranges (High Gain Data and Low Gain Data). Figure 6 shows the spectrum of gamma rays in the low energy range from 0.1 to 3 MeV (High Gain Data). Gamma-ray events are collected every 17 seconds and accumulated under the regular observation from Dec. 14, 2007 to Feb. 17, 2008. Those spectra were measured with anti-coincidence operation of BGO and plastic scintillators.

SELENE GRS observes gamma-ray peaks of elements: potassium, thorium, uranium, oxygen, magnesium, aluminum, silicon, calcium, titanium, iron, and germanium. We have acquired the global measurements of gamma-ray spectrum from the lunar surface, and thus elemental composition measurements were made for the lunar entire surface. Individual net area of the peaks is related to the concentration of elements. Typical peaks are attributed to natural radioisotopes of K, Th and U, and some other major elements such as O, Al, and Si. There are an outstanding peak of annihilation gamma rays at 511 keV and several broad peaks from Ge with a sawtoothed shape showing a high energy tail. Ge peaks are produced through the inelastic scattering interaction of fast neutron with Ge nuclide in the Ge detector by the addition to their characteristic line gamma rays. Strong sawtooth peaks are 596, 692, 834 and 1039 keV, which make peak analyses of other elements near those energies difficult.

In the period when the spectrum was measured, however, as long as the peak position of 511 keV annihilation gamma ray were monitored every 2 minutes, its position was quite stable with the precision of about 0.4 keV (1 ADC channel in high gain spectrum), so the fine tuning to signal gain in the spectra was not applied when accumulating. The other data corrections that should be applied to spectra before accumulation are the correction to spacecraft altitude variation and the correction to cosmic ray flux variation, but being not applied to the spectra in Fig.6. Real counting interval for the spectra was about 1027 hours and the corresponding dead time in the measurement was about 23%.

Fig. 6. Energy spectrum of gamma rays with energies up to about 3 MeV from high gain data sets measured by SELENE GRS.

The very first energy spectra of gamma rays measured by a Ge detector are shown in Fig. 7. They have been accumulated for the first two months of the observation for the entire lunar surface. To compare the precision of SELENE GRS with those by past observations, an energy spectrum obtained by Lunar Prospector is also shown³.

Because of its excellent energy resolution of the Ge detector, most of sources of gamma-ray lines are identified. Especially, lines from major elements on the Moon, O, Mg, Al, Si, Ca, Ti, and Fe, as well as natural radioactive isotopes such as 40K, 232Th, 238U were clearly observed. Those lines cannot be resolved with observations with scintillators. For example, with a scintillator, two Fe peaks at 7.6 MeV are summed as one, and the Th peak at 2.615 MeV has an interference from a strong background peak at 2.754 MeV, as can be seen from Fig. 7. The poor energy resolutions require a spectrum deconvolution, which can be a source of uncertainty. The uniquely identified peaks by the Ge detector are essential in the complex mixed gamma-ray field to derive elemental abundances with high precision.

Fig. 7. Comparison of energy spectra obtained by SELENE GRS and Lunar Prospector GRS.

The energy spectra include not only gamma rays induced
by high-energy cosmic rays in lunar surface materials, but also 
gamma rays from GRD itself and its surrounding materials, and 
the spacecraft body as background gamma rays. With the 
individual spectra from different lunar regions, evaluation of 
the instrumental backgrounds will be possible because Fe and 
Th contents are known to be small in the highlands but Ca 
and the Al, in contrast, are relatively low in the maria.

Clear peaks emitted from natural radioisotopes of $^{40}$K, $^{232}$Th, and $^{238}$U are seen in each energy spectrum of gamma rays from the whole Moon. The local difference among their concentrations over the lunar surface crust is very important to 
deduce constraint for the formation and thermal histories of 
the lunar crust. The intensities of $^{208}$Tl ($^{232}$Th chain) 
gamma ray, as a typical example, are plotted in Fig. 8 for 
each quadrant sphere of nearside and farside of northern 
hemisphere of the Moon. It shows a clear difference of Th 
intensity among the quadrant spheres. The intensity of $^{208}$Tl 
gamma rays (2614.5 keV) from the northern nearside region 
is the highest among them, while northern farside has the 
lowest one among these four spherical regions. It is 
consistent with the observation made by Lunar Prospector 
(Lawrence et al., 1998), in which it is reported that both of K 
and Th are primarily concentrated within and around the 
western-most maria on the nearside.

Global map of Th gamma-ray counting rate which 
roughly corresponds to relative Th abundance was obtained 
from the GRS on SELENE. Figure 9 shows a global map of 
Th gamma-ray intensity. These data have undergone almost 
no corrections for gain, cosmic ray variations and 
symmetric response of the GRS instrument. The most 
rich-area is within Procellarum KREEP Terrain. The 
highest Th abundances on the Moon are located around the 
Inbrium basin region. South-Pole-Aitken (SPA) basin is 
modestly elevated in Th relative to the rest of the farside. The 
counting rate in the Northern nearside being rich in basalts is 
higher than that in farside highland terrain abundant in 
anorthosites. SELENE GRS has also measured global maps 
of U and K. Those maps of natural radionuclide distributions 
are quite similar each other. U, Th and K are important 
elements for tracing the thermal history and evolution of the 
Moon. They are enriched in a material called KREEP (potassium (K), rare earth elements (REE) and phosphors 
(P)) and they are thought to be formed between the crust and 
mantle. It is thought that in the solidification process of 
Lunar Magma Ocean, the last material to crystallize was rich 
in those elements that do not substitute easily into the crystal 
lattice of the major rock forming minerals. The global 
mapping of the trace elements provides further insight into 
the mechanisms underlying the distribution of various 
elements about the Moon, in particular, the excavation and 
deposition of KREEP through lunar impact events.

4. Conclusion

SELENE (KAGUYA) Gamma-Ray Spectrometer (GRS) 
consists of a large germanium crystal cooled actively to 80 
K$^{0.5}$. Lunar gamma-ray spectra were collected every 17 
seconds. The spectrum of lunar gamma rays was 
During the observation period no solar proton events 
which may cause large increases in counting rates and 
distortion of the spectra, have been observed. Many peaks of 
K, Th, U, O, Mg, Al, Si, Ca, Ti Fe, and Ge features were 
observed in the energy spectrum of gamma rays in Fig. 6 and 
7. Some of the gamma-ray lines observed in the spectra are 
also produced from the material in or near the GRS. The data 
presented here have undergone almost no corrections for gain, 
cosmic ray variations and asymmetric response of the 
GRS instrument.

Global mapping data of energy spectra, counts of gamma 
rays indicating elemental concentrations and absolute 
concentrations of chemical elements in the lunar surface will 
be provided after a careful calibration and correction of data, 
and a vigorous simulation of gamma-ray emission from the 
Moon. Joint study on the geological survey by GRS, Lunar 
Imager/Spectrometer (LISM) and other instruments will be 
very useful to perform cross calibration and reference and to 
improve the reliability of their results. Together with the 
cooperative programs of several scientific instruments 
onboard SELENE, geochemical maps should give insight 
into the nature of the formation and evolution of the Moon, 
and the detailed horizontal and vertical structure of the Moon. 
Moreover, the global maps of chemical abundance on the 
lunar surface obtained by the GRS are essential for the
utilization of lunar resources in order to make the progress of human activities in space.

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