X-RAY FLUORESCENCE SPECTROMETER (XRS) ON KAGUYA : CURRENT STATUS AND RESULTS. T. Okada[1], H. Shiraishi[1], K. Shirai[1], Y. Yamamoto[1], T. Arai[1,2], K. Ogawa[1], M, Kato[1], M. Grande[3], and the SELENE XRS Team, [1]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan. (okada@planeta.sci.isas.jaxa.jp), [2]Solar Observatory, National Astronomical Observatory of Japan, Mitaka, Tokyo, Japan., [3] Institute of Mathematical and Physical Sciences,University of Wales, Aberystwyth, UK.

Introduction: X-ray fluorescence spectrometer (XRS) for major elemental composition mapping of lunar surface is carried on Kaguya, the Japanese lunar polar orbiter SELENE (SELenological and ENgineering Explorer), which continues its observation in the circular orbit around the Moon. Kaguya conducts 15 experiments including XRS.

Remote XRF spectrometry during the Apollo 15 and 16 missions has proven that major elemental composition is able to be determined through the method for atmosphere-free planetary surface [1]. Solar X-rays irradiate planetary surface to excite X-ray fluorescence characteristic of major elements at the uppermost layer of surface materials to the depth of several tens of micrometer. Temporal variation of intensities and spectral profiles of solar X-rays affects those of XRF off the planetary surfaces as well. Therefore mapping of major elemental composition from the orbit requires concurrent monitoring of solar X-rays. It also needs a appropriate interpretation for quantitative elemental analysis for its angular and surface roughness effects.

A key target of Kaguya is surface mineralogy and major elemental composition using Visible-to-Near-Infrared, X-ray and gamma-ray spectroscopy. XRF spectrometry aims at mapping major elemental composition, especially in Mg, Al, and Si with complete coverage except at polar region, and in Ca, Ti, and Fe only during solar flares. To achieve them, XRS is requested to have high sensitivity in 1-8 KeV range and footprint size of 20km by 20km from 100km circular orbit (energy resolution less than 180eV at 5.9KeV and almost 100 cm^2 detection area). Thus it consists of CCD-based main detector with a direct monitor of solar X-rays as well as XRF calibrator aboard [2-4]. We present here the original scientific objectives, instrumentation of the XRS, as well as its current status around the lunar orbit.

Main Scientific Objectives: Scientific objectives of the XRS observation are (1) global mapping of major elements of lunar surface materials except for polar regions during day time observation, (2) understanding the physical processes of lunar X-ray illumination in the night time that happens by impact of solar wind particles and comic rays as well as natural radioactivity, and (3) regional variation of surface microscopic roughness as a result of particle size effect on XRF.

Lunar XRF experiments have mapped only about 10 % of the lunar equatorial regions during the Apollo 15 and 16 missions in 1971-1972 and implied that lunar maria are covered with lava flows in basaltic composition and lunar highlands are dominantly occupied with aluminous anorthosetic materials [1]. Tsiolkovsky crater shows more mafic, mare-basaltic composition relative to its surrounding anorthosetic highlands. Impact ejecta of Picard crater that is located even in the mare basin reveals remarkably mafic composition in comparison to the average composition of Mare Crisium. The effective spatial resolution of the Apollo XRF map is less than 30km after compilation of data obtained from several orbits.

Kaguya's elemental composition mapping also aims at identification of materials from deep interior when observing the central peaks of craters and impact ejecta. Regional variation of basement rock composition will be informed as well as exposed mantle materials. Investigation of crust and mantle differentiation processes, evolution of lunar highland crust, and magnesium number of the lower crust and mantle will be the main targets.

XRS Instrument: The XRS instrument consists of a main detector to observe X-rays off the lunar surface, XRF-A, a direct solar X-ray monitor and an onboard XRF calibrator with standard sample, SOL-BC, and the electronics, XRS-E.

We adopted charge-coupled devices (1-inch square sized, 1K by 1K pixels, full-frame transfer type, buttable shape, prepared by Hamamatsu Photonix, K.K.), ultra-thin beryllium light-tight window in 9 micron thick, 3 mm-pitch latticed collimators to limit the FOV in 12 x 12 deg, advanced thermal design to keep CCD chips cool with passive radiation, and the 60MIPS and 32 bit fast RISC onboard computer (SH-OBC), of voting majority technique to improve radiation tolerancy.

In the preflight test, XRS has higher energy resolution of 150 to 180 eV at 5.9KeV, and large detection area of $100cm^2$ by using array of 16 CCD chips. Since the allocation of telemetry is limited in 4Kbytes/sec, the XRS has functions to extract only X-ray events from all the readout data of CCD at 125KHz, to classify the grade of each X-ray event, and to produce X-ray energy spectrum by using the onboard logic circuits of FPGA and the software program in the SH-OBC.

Degradation of CCD Performance perhaps due to Radiation Damage: The XRS worked well in its functions of electronics, power supply, thermal control as well as onboard data handling functions of FPGA logics and the software. However, there was found some degradation of CCD performance: larger numbers of unproperly long tailing events than expected, possibly due to defects at the charge transfer layer inside the CCD chip by radiation damage, and by numerous events of cosmic ray impacts. The XRS has experienced much more severe radiation condition than originally designed. The original trajectory to reach the Moon is direct insertion into the lunar orbit. But the trajectory has been changed to add 2 and a half round phasing orbit around the Earth before LOI, so that it passed terrestrial radiation belt three times to be irradiated by one order of magnitude higher level.

To make sure the hypothesis, we performed proton radiation test in the laboratory in Tsukuba Space Center of Japan Aerospace Exploration Agency. We found that the trailing phanomena found on CCD becomes remarkable with tolerance of > 10^8 [protons/cm^2] for relatively low energy of protons (0.3MeV). Typical condition occurred on the XRS is explained with higher tolerance by several factor. Details of this laboratory test will be shown in the future papers. In this condition, those data from most proximate pixels to the readout point of CCD are less influenced due to shorter transfer length but with much small effective area.

In flight operation test, we confirmed that performance of CCD becomes better without trailing pnenomena at lower temperature below -90 ^oC. Now we conducts low-temperature operation using thermoelectric cooler installed inside the CCD package.

Historically Quiescent Solar Activity: The XRS observes the X-rays excited by solar X-rays and calibrates its detector performance using the line spectra of them. Unfortunately, the solar activity has been in the very quiescent level during most of the periods since the Kaguya's launch. Solar X-ray intensity monitor data of GOES (Geostationally Orbiting Environmental Satellites) shows its level below detection limit for most of duration. The sunspot number is almost always zero, with only 10 sunspot groups have occurred in a first year of 24^{th} solar cycle after announced to start .

Historically faint solar activity, lowest in a century, severely affected the XRS experiments. First of all, X-ray illumination off the Moon is too faint to detect in a proper signal to background level sufficient for instrumental calibrations and for examination of detector performances. This is an essential problem since the XRS does not carry radioactive or electrically-active calibration sources aboard. In the last solar minimum, sunspot number and solar X-ray intensity level was relatively enhanced by one order of magnitude. The new solar sycle 24 still remains waited to come regularly. It is more than one year delayed compared to spaceweather forecasts.

Lunar X-ray Detections: Detections of lunar X-rays are reported with XRS during the periods when solar X-ray monitor SOL-C simultaneously detected X-rays off a standard sample plate. As mentioned before, data from those pixels proximity to the readout point of CCD is used as proof of lunar X-ray detection.

On 13 Dec 2007, or on 27-29 Mar 2008 are some examples of lunar X-ray detection, probably excited by solar X-rays. Basically the solar activity has been not so strong, below B-class, and the signal to background ratios are limited. Hence, integration of thousands seconds, that is, the along-track distance corresponding to spatial resolution is 1-5 x 10^3 km is required to obtain statistically significant amout of photons.

It is important to be noted that XRF excitation is not only by solar X-rays but also by other processes such as charged particle events. For example, on 23 Nov 2007 are detected the enhancement of events but no solar flares were monitored with GOES solar X-ray monitor. The enhancement was found even in the night time. This implies that sporadic excitation by impacts of protons or electrons.

Interpretation methods by XRF on lunar soils: The XRS experiments are highly dependent on solar activity, which has been in the solar minimum in 2007 and X-ray activity has been in "very low" level (under A0-Level). Furthermore, the beta angle (the angle of the Sun to the center of the Moon to the spacecraft) is rather high so that the incident angle of solar X-rays is larger than 60°, which is under unproper condision for XRF spectrometry. Therefore quantitative elemental composition is yet to be obtained so far.

As compared to the laboratory experiments is that reduction of XRF excitation was found at a relative ly large phase angle by several to an order of magnitude. This is typical phenomenon of XRF at the sandy surface like lunar regolith [5]. In 2008, the next solar sycle has begun but solar activity appears to soften with some occurrences of C-class solar flares. After February, the beta angnle condition becomes suitable for XRF spectrometry. The elemental determination and its mapping will be expected to start at that time.

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