PROCEEDINGS OF SCIENCE

SOlar Neutron and Gamma-ray Spectrometer (SONGS)

Kazutaka Yamaoka,[a,*] **Hiroyasu Tajima,**[a] **Kikuko Miyata,**[b] **Toyoki Watabe,**[c] **Kazuya Ito,**[d] **Takuya Miyazawa,**[e] **Tetsuya Kudoh,**[d] **Kazuhiro Nakazawa,**[f] **Satoshi Masuda,**[a] **Koichi Tani,**[g] **Masaki Arai,**[g] **Satoshi Hatori,**[h] **Kyo Kume,**[h] **Satohi Mizushima,**[h] **Hiromitsu Takahashi**[i] **and Kyoko Watanabe**[j]

[a] *Institute for Space and Earth Environmental Research (ISEE), Nagoya University, Furo-cho Chikusa-ku, Nagoya, Japan*

[b] *Graduate School of Engineering, Meijo University, 1-501 Shiogamaguchi, Tempaku-ku, Nagoya, Japan*

[c] *Institute of Liberal Arts and Sciences, Nagoya University, Furo-cho Chikusa-ku, Nagoya, Japan*

[d] *Technical Center, Nagoya University, Furo-cho Chikusa-ku, Nagoya, Japan*

[e] *Okinawa Institute of Science and Technology (OIST), 1919-1 Tancha, Onna-son, Kunigami-gun, Okinawa, Japan*

[f] *Kobayashi-Maskawa Institute for the Origin of Space and Universe (KMI), Nagoya University, Furo-cho Chikusa-ku, Nagoya, Japan*

[g] *Jinsei Inc., 1-7-14 Osu, Naka-ku, Nagoya, Japan*

[h] *The Wakasa-wan Energy Research Center (WERC), 64-52-1 Nagatani, Tsuruga, Japan*

[i] *Graduate School of Science, Hiroshima University, 1-3-2 Kagamiyama, Higashi-Hiroshima, Japan*

[j] *National Defense Academy of Japan, 1-10-20 Hashirimizu, Yokosuka, Japan*

E-mail: yamaoka@isee.nagoya-u.ac.jp

Particle acceleration mechanisms of protons and heavy ions in solar flares and coronal mass ejections (CMEs) are still unknown issues. Neutrons can be unique observation probes since they are hardly affected by solar and interplanetary magnetic field. However, little progress has not been made in previous neutron observations due to its insufficient sensitivity in ground-based observatories. To over come such situation, we have launched new space mission dedicated for solar neutron observations, so-called SOlar Neutron and Gamma-ray Spectrometer (SONGS). This detector consists of multi-layered 256 plastic scintillator bars and 12×12 GAGG(Ce) scintillator array readout by SiPMs to track cosmic-ray interactions in three dimensions. In this configuration, it is sensitive to both fast neutrons (30–120 MeV) and soft gamma-rays (0.1–3 MeV). In this paper, we report on scientific motivation, instrumental details, and development status of the SONGS mission.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)1341

1. Introduction

The Sun is an ideal high-energy object for understanding mechanisms of particle acceleration seen in several astronomical sites because it is easily accessible from the Earth. It is well known that solar transient phenomena, e.g. solar flares (SFs) and coronal mass ejections (CMEs), accelerates charged particles up to a few GeV and sometimes reaches to the Earth, but we do not know when, where and how particles, especially protons and heavy ions, are accelerated. Huge SF and CME events could significantly affect infrastructure on the Earth, e.g., Ground Positioning System (GPS) and power plants, and consequently human lives. Understanding of mechanisms of solar flare occurrence and particle acceleration are becoming more important day by day to predict the space weather.

The Sun has been mainly observed through electro-magnetic waves and charged particles (protons and electrons) so far. Solar neutron observation can be another important probe to understand ion acceleration mechanisms, but little progress has not been made in observations since its discovery in 1980 [1]. Ground-based neutron monitors and telescopes have only detected 12 sample associated with solar flares for about 40 years probably due to attenuation by the Earth atmosphere and less detection sensitivity [2] [3] [4]. From space, the Japanese SEDA-AP experiment on the International Space Station observed more than 40 sample associated with solar flares for 9 years since 2009 [5] [6], and the MESSENGER mission has also detected several solar neutron candidates in the Mercury orbit close to the Sun [7]. To fill the gap we do not have any space instruments dedicated for solar neutron observations, we have started a project aimed for solar neutron and gamma-ray observations from space using micro-satellites. The first mission we have launched on February 2016 is 50-kg ChubuSat-2 satellite [8]. However, we have not successfully operated the satellite and the solar neutron detector in orbit. To increase launch opportunities, we started a new project called as Solar Neutron and Gamma-ray Spectrometer (SONGS) [9] for microsatellites since 2018. The SONGS mission originally started as the 3U CubeSat mission, and the current configuration is changed to one of the payloads onboard the JAXA innovative satellite for technology demonstration [10] or onboard the ISS modules. In this paper, we will describe details of the SONGS mission for the CubeSat.

2. Instrument Overview

The SONGS consists of stacked rod-shape plastic scintillators with 16 units×16 layers and 12×12 GAGG(Ce) scintillator array (see Figure 1). The size of each plastic scintillaor bar is 3.95×3.95×64 mm and each GAGG crystal has a dimension of 6 mm cubic. The plastic scintillators are used for neutron detection through elastic scattering process of neutrons with hydrogen atoms in the scintiilator, and also work as a scatterer in the Compton scattering process of gamma-rays, while a GAGG pixel array is used as an absorber of scattered gamma-rays in the plastic scintillator. Combination of the two kinds of scintillators can work as a Compton camera. The plastic scintillator is surrounded with the anti-coincidence detector with six faces to reject charged particles. The scintillation light from all the scintillators are read out with Multi-Pixel Photon Counter (MPPC) and converted to photo-electrons and amplified by a factor of 10^6 in the MPPCs for operating voltage of ~55 V. For plastic scintillator bars, signals are read out from both sides to determine the position along bars. The resultant charge pulse is sent to the front-end circuit boards (FEC1 and FEC2), and all the MPPC signals are processed by 16-channel Application-Specified Integral Circuit (ASIC) IDE3380 [11] with very low power in the FEC1, and their signal pulse heights are digitized by 12-bit Analog-to-Digital Converter (ADC) installed to the ASIC. The digitized data are sent to the FEC2 and compressed by the FPGA. All the data from in total 704 MPPC signals are collected to the Data Processor (DP) board. The DP controls the trigger and judges an occurence of solar flare based on deviation from the statistical fluctuation of the counting rate. The Mission OnBoard Computer (MOBC) and Power Supply (PS) board has an interface to the satellite bus system, and telemetry/command are processed in the MOBC. The Low Power Wide Area-network (LPWA) has also been equipped to the SONGS, and if a strong solar flare occurs and is detected by the SONGS, a flash report is issued to the ground. Anyone with terminals can receive the SONGS detection information about the solar flare. Figure 2 shows overview of the system, and characteristics of the SONGS is summarized in Table 1.

Table 1: Characteristics of the SONGS

Size	10 cm×15 cm×15 cm
Weight	3 kg
Power	~6 W
Detector	256 plastic scintillator bars + 12×12 GAGG array
	+ 6 anti-coincidence detectors, read out by 704 Si PMs
Energy Range	30–120 MeV for neutrons
	0.1–3 MeV for gamma-rays
Energy Resolution (FWHM)	∼23%@ 56 MeV for neutrons
	∼7%@0.662 MeV for gamma-rays
Point Spread Function (FWHM)	∼40 degrees for 1 MeV gamma-rays
Detection Efficiency	∼1% for both neutrons and gamma-rays
Additional Function	Prompt notification of solar flare detection via
	LPWA communication system.

3. Bread Board Model (BBM) and Engineering Model (EM)

To assemble the sensor component and verify the sensor performance, we have developed a bread-board model (BBM). The BBM consists of 64 plastic scintillator bars and 4×4 GAGG array. The plastic scintillator bars with rough surface are wrapped by aluminized mylar and both sides of central part (8 units × 4 layers) were read out by the Hamamatsu MPPC with 3×3mm area and a custom-made signal processing board with 4 ASICs and 1 FPGA which can process 64 channels independently. The GAGG array was fabricated by C&A corporation in Japan and the white reflector $BaSO_4$ is used between crystals. It is optically coupled to the Hamamatsu MPPC 4×4 array and read out by the IDEAS SIPHRA board with 1 ASIC [11]. Figure 3 shows overall picture of the BBM.

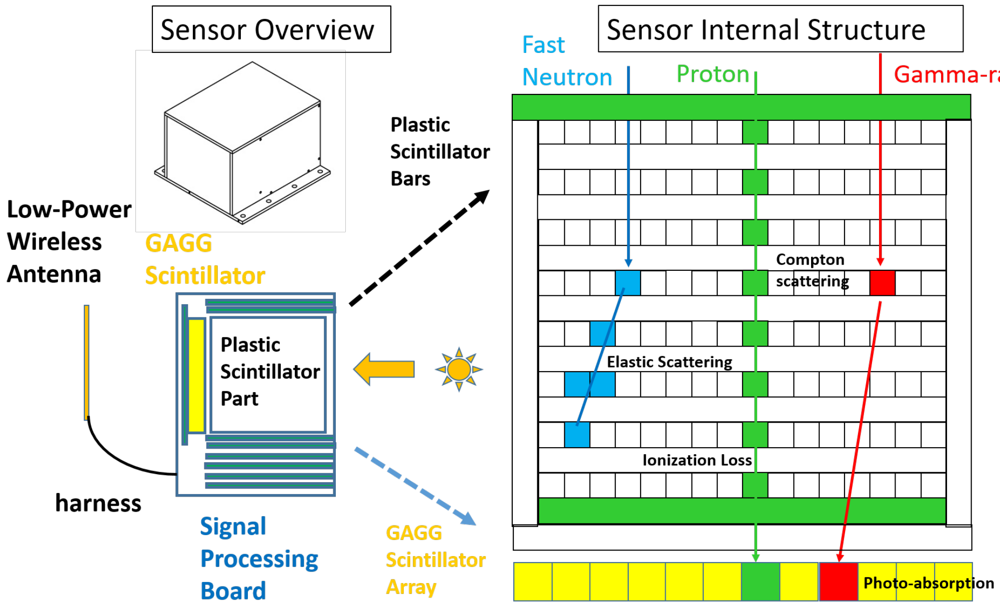

Figure 1: SONGS Structure. Left upper: SONGS appearance. Left Lower: Cross-sectional View of the SONGS. Right: Cross-sectional view of Sensor part and difference in detection of various radiation.

For the plastic scintllator, we verified the position determination capability along the bar direction using 662 keV gamma-rays and cosmic-ray muons and derived 5.0–7.5 mm Full-Width Half-Maximum (FWHM) position resolution. After that, we irradiated proton beam at synchrotron accelerator facility of the Wakasa-wan Energy Research Center (WERC) because neutrons are converted to recoiled protons in the elastic scattering. The proton energy was changed from 11.8 MeV to 46.0 MeV by putting polyethylene plate with various thickness between the beam exit and detector surface. The FWHM energy resolution was estimated to 14.6 % for 46.0 MeV protons, which is better than that of SEDA-AP (see left panel of Figure 4). Taking into account an averaged recoiled angle of ∼25 degrees and incident angle determination accuracy of 10.8% from the measurement, we estimated the energy resolution to be 22.8% for 56 MeV neutrons. This value corresponds to the time difference of 158 seconds on the Sun, which can distinguish whether neutrons originates from either the SF or the CME.

For the GAGG array, we have irradiated various gamma-ray isotopes covering the energy range from 59.5 keV to 1274 keV. The GAGG+MPPC array detector response is affected by several effects. One is the MPPC saturation effect in photo-electron numbers because GAGG scintillator has a relatively high light yield (several ten thousand per MeV). The other is a light leak from one to another neighboring pixel because isolation by reflectors between pixels is not perfect. We have corrected for both effects, and separated multi-hit events from only one reaction events, and evaluated the energy and position information required for Compton camera. Right panel of Figure 4 shows the energy resolution with/without any light leak correction, and we have obtained a good FWHM energy resolution of ∼7% at 662 keV after the correction [12] and almost follows the relation of $Q^{-1/2}$ where Q is the created charge, determined by statistical fluctuation of the photo-electron

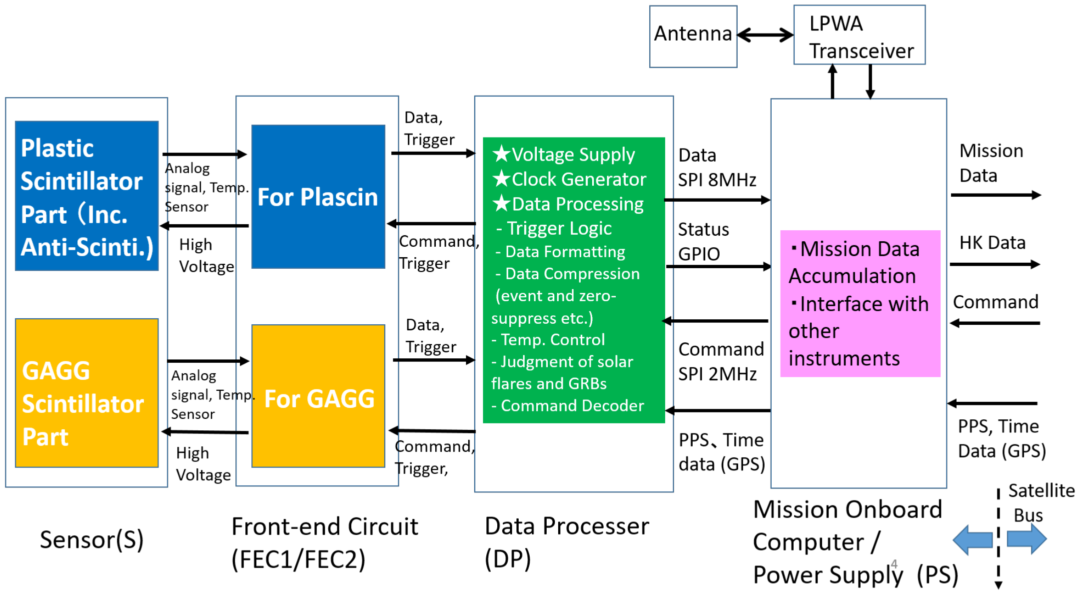

Figure 2: Block diagram of the SONGS System. The SONGS consists of Sensors, Signal Processing boards (FEC1/2, DP, and MOBC/PS), and Low Power Wide Area-Network (LPWA) communication system.

numbers.

As a next step, we are constructing theE engineering model (EM) where most of the electronics and sensors are flight-model (FM) equivalent. The difference between the EM and FM is number of layers of plastic scintillators: 8 for the EM and 16 for the FM. Figure 5 shows the picture of the EM of the plastic scintillator part including stacked scintillators and anti-coincidence plates and aluminum housing structure in comparison with the ChubuSat-2 radiation detector (RD) with a dimension of 18 cm×15 cm×15 cm. Within this year, this model will be verified via the detector performance test and vibration/thermal vacuum test, and some modification will be done later (so-called EM2) before the FM construction.

4. Summary

We are now developing a novel fast neutron and gamma-ray detector with a small size, light weight and low power for microsatellites and aiming at the launch by the JAXA rapid innovative payload demonstration satellite around 2025 which corresponds to almost solar maximum. This detector is being constructed in-house within universities in collaboration with engineering/science people and technical staffs. We are also looking for opportunities to operate our detector in the Moon and Mars orbit to detect an evidence for water resources as well as radiation monitor.

Acknowledgments

This research has been financially supported by Toyoaki Scholarship Foundation, Daiko Foundation, Foundation of Public Interest of Tatematsu, Japan Keirin Autorace Foundation (JKA) and its

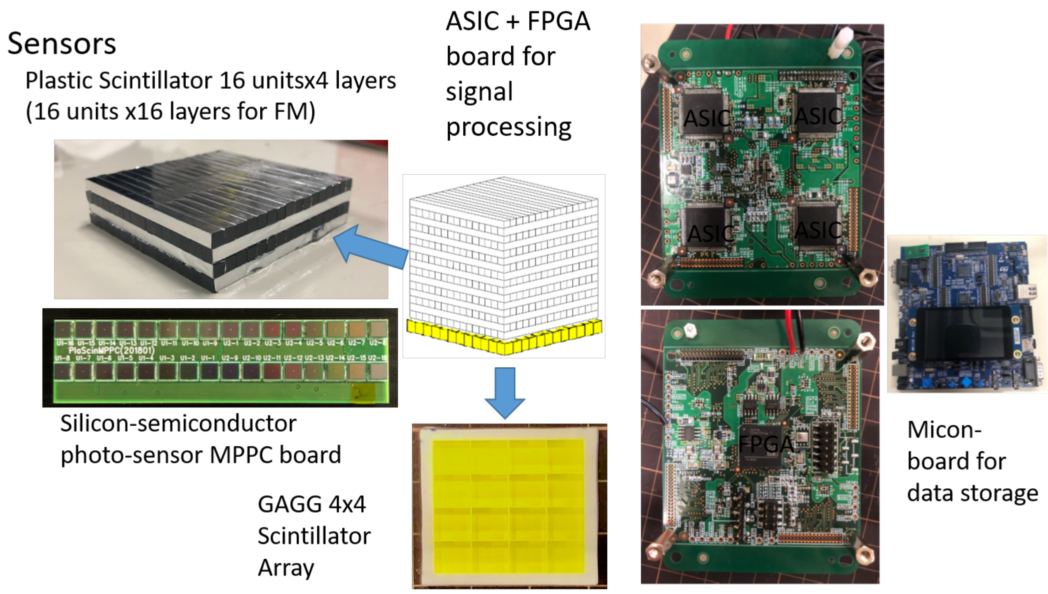

Figure 3: Picture of the Bread Board Model (BBM). The BBM consists of plastic scintillator with 4 layers and 4×4 GAGG(Ce) array, readout with the MPPC board. 64 channels from MPPC signals can be processed by an ASIC+FPGA board. It is developed for testing of detector performance.

promotion funds from AUTORACE, and JSPS Grant-in-Aid for Scientific Research (KAKENHI) Grant Number JP18H03700 (KY).

References

[1] Chupp, E. L. Forrest, D. J., Ryan, J. M., et al., “ A Direct Observation of Solar Neutrons Following the 0118 UT Flare on 1980 June 21, ” Astrophysical Journal 263, L95-L98 (1982).

[2] Matsubara, Y., Muraki, Y., Masuda, K, et al., “ Observation of Solar Neutrons by the World-Wide Network of Solar Neutron Detectors, ” Proceedings of the 26th International Cosmic Ray Conference, 42 (1999)

[3] Sasai, Y., Nagai, Y., Itow, Y., et al., “ Performance of the SciBar Cosmic Ray Telescope (SciCRT) toward the Detection of High-Energy Solar Neutrons in So-lar Cycle 24, ” Earth, Planet and Space, 66, 130-137 (2014).

[4] Yu, X. X., Lu, H., Chen, G. T., Li, X. O., Shi, J. K., Tan, C. M., “ Detection of solar neutron events and their theoretical approach, ” New Astronomy 39, 25-35 (2015)

[5] Muraki, Y., Koga, K., Goka, T., Matsumoto, H., Obara, T., Okudaira, O., Shibata, S., Yamamoto, T., “Measurement by FIB on the ISS: Two Emissions of Solar Neutrons Detected?, ” Advances in Astronomy, article ID 379304 (2012)

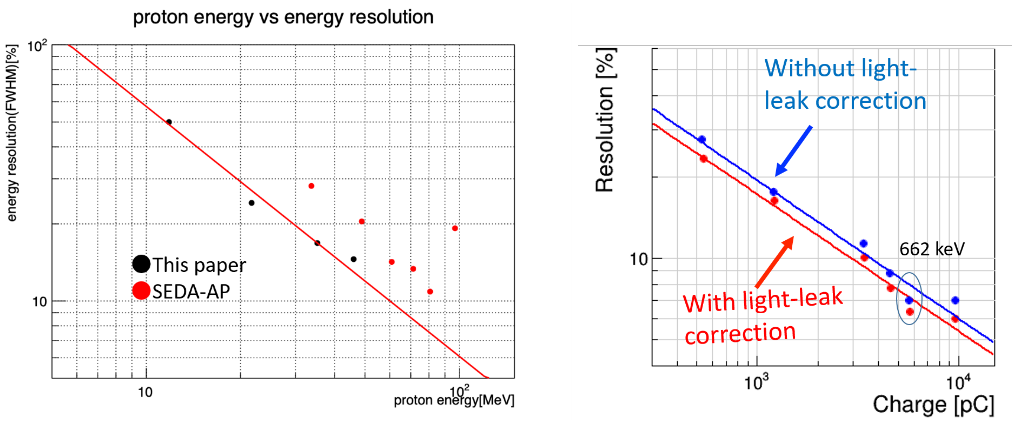

Figure 4: Left: Energy resolution of plastic scintillator with 4 layers for protons in comparison with that of SEDA-AP (red). Right: FWHM energy resolution of the GAGG(Ce)+MPPC 4×4 Array with (red)/without (blue) light leak correction.

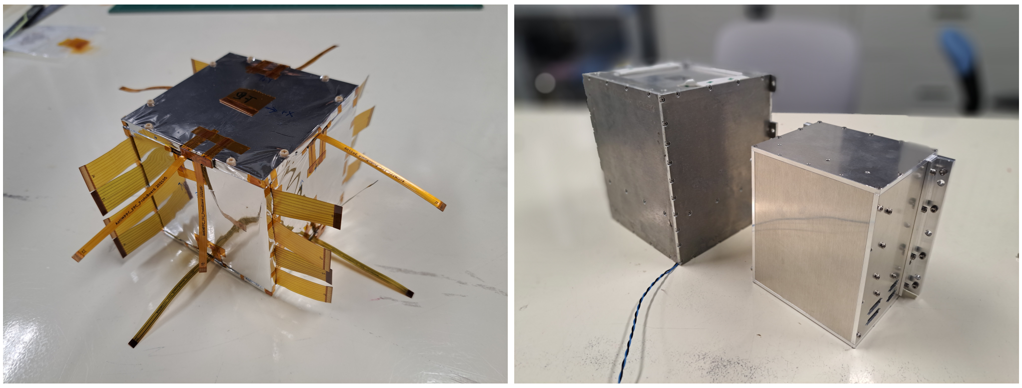

Figure 5: Picture of the Engineering Model (EM). Left panel: Structure of the plastic scintillator part. Right panel: Housing structure in comparison with ChubuSat-2 Detector.

[6] Koga, K., Muraki, Y., Masuda, S., Shibata, S., Matsumoto, H., Kawano, H., “Measurement of Solar Neutrons on 05 March 2012, Using a Fiber-Type Neutron Monitor Onboard the Attached Payload to the ISS,” Solar Physics 292 (8), 115-130 (2017)

[7] Lawrence, D. J., Feldman, W. C., Goldsten, J. O., Peplowski, P. N., Rodgers, D. J., & Solomon, S. C., ”Detection and characterization of 0.5–8 MeV neutrons near Mercury: Evidence for a solar origin,” Journal of Geophysical Research Space Physics 119 (5), 150-5, 171 (2014)

[8] Yamaoka, K., Babazaki, Y., Hayashi, Y., et al., “Solar Neutron and Gamma-ray Monitor on the ChubuSat-2 Satellite,” Transaction of the Japan Society for Aeronautical and Space Sciences (JSASS) Aerospace Technology Japan 14(ists30), Pf_141-146 (2016)

[9] Yamaoka, K., Tajima, H., Miyata K., et al., “Solar NeutronSpectrometer onboard a 3U

CubeSat, ” Transaction of the Japan Society for Aeronautical and Space Sciences (JSASS) Aerospace Technology Japan 19 (ists32), 354-359 (2021)

[10] The JAXA innocative satellite Technology Demostration Program: https://www.kenkai.jaxa.jp/eng/research/innovative/innovative.html

[11] Meier, D., Ackermann, J., Olsen, A., et al., “SIPHRA 16-Channel Silicon Photomultiplier Readout ASIC,” In: Proc. AMICSA&DSP 2016, 12-16 June 2016, Gothenburg, Sweden (2016)

[12] Nobashi, D., Yamaoka, K., Tajima, H., Ito, K., Performance evaluation of GAGG(Ce)/LFS scintillator + MPPC array readout with ASIC, ” Nuclear Instruments and Methods in Physical Research Section A, 986, 184611 (2021)