Solar Neutron and Gamma-ray Monitor on the ChubuSat-2 Satellite

By Kazutaka YAMAOKA, Yasunobu BABAZAKI, Yuki HAYASHI, Hidehiro KANEDA, Taishi KATSURAGAWA, Hiroaki KAWAHARA, Takuma KOKUSHO, Shin KUBO, Kazunari MATSUNAGA, Koji MATSUISHITA, Kikuko MIYATA, Takuya MIYAZAWA, Hosei NAGANO, Yasutaka NARUSAWA, Masaki NISHINO, Sosuke NODA, Shinji OSEKI, Masaaki SADAMOTO, Asami SUZUKI, Hiroysu TAJIMA, Keisuke TAMURA, Hitotaka TANAKA, Hiroya TANAKA, Masato TAGUCHI, Dao ngoc hanh TAM and Toyoki WATABE

1) Division of Particle and Astrophysical Science, Graduate School of Science, Nagoya University, Nagoya, Japan
2) Institute of Space-Earth Environmental Research (ISEE), Nagoya University, Nagoya, Japan
3) Department of Energy Engineering and Science, Graduate School of Engineering, Nagoya University, Nagoya, Japan
4) Clear Pulse Co., Ltd., Tokyo, Japan
5) Technical Center, Nagoya University, Nagoya, Japan
6) Department of Aerospace Engineering, Graduate School of Engineering, Nagoya University, Nagoya, Japan
7) Department of Mechanical Science and Engineering, Graduate School of Engineering, Nagoya University, Nagoya, Japan
8) Department of Electrical Engineering and Computer Science, Graduate School of Engineering, Nagoya University, Nagoya, Japan

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The ChubuSat is a Japanese microsatellite technology demonstration mission jointly developed by Nagoya university, Daido university, and medium or small-sized aerospace industrial companies in the Chubu area of central Japan. ChubuSat-2 is the second ChubuSat following ChubuSat-1 which was launched by the Russian DNEPR rocket on November 6, 2014. It was selected as one of the four piggyback payloads of the X-ray astronomy satellite ASTRO-H in 2014 summer, and will be launched by the H-IIA rocket from Japan Aerospace Exploration Agency (JAXA) Tanegashima Space Center (TNSC) in winter season of fiscal year (FY) 2015. The ChubuSat-2 mission is devoted to monitoring neutrons and gamma-rays in the ASTRO-H orbit which can be noise sources for ASTRO-H X-ray and soft gamma-ray observations. The mission involves solar neutron observations which were originally proposed by graduate students who joined the leadership development program for space exploration and research, a program for leading graduate schools at Nagoya University. In this paper, we describe the outline of the ChubuSat-2 satellite and the details of the mission instrument, the radiation detector (RD).

Key Words: Micro-satellite, ChubuSat, Radiation Monitor, Neutron, Gamma-ray, Solar Physics

1. Introduction

The ChubuSat is a series of 50kg-class micro-satellites developed by a collaboration among Nagoya University, Daido University, and aerospace industry companies (Monozukuri Aerospace Support Technology Team: MASTT,1) around the Chubu region in Japan. This region including Nagoya city is at the center of Japan, and it is the core region of Japanese aerospace industries. The aim of this project is to form the basis of industrialization of the micro-satellite business and revitalize the Chubu region. Another purpose is to foster global human resources with specialized knowledge about the aerospace field utilizing development of the ChubuSat satellite.

The first satellite ChubuSat-1,2) (or “Kinshachi-1” which means golden grampus which is the roof monument of the Nagoya castle.) carries two kinds of sensors: optical and infrared cameras to monitor natural disasters such as forest fires on the Earth and space debris. It was successfully launched by a DNEPR rocket from Yasny in Russia on November 6, 2014. Some bus instruments were nominally turned on and the telemetry was sent to the ground, but a power shortage occurred because it took some time to stabilize the satellite at the nominal altitude after launch. We are still making an effort to recover this mission.

Following the ChubuSat-1 satellite, ChubuSat-2 was selected by the Japan Aerospace Exploration Agency (JAXA) as one of the four piggyback payloads of the X-ray astronomy satellite ASTRO-H,3) in 2014 summer. It is planned for launch by the H-IIA rocket from the JAXA Tanegashima Space Center in winter of FY 2015.1) The main mission of ChubuSat-2 is monitoring the radiation environment in low Earth orbit to support X-ray and gamma-ray observations with ASTRO-H. We have adopted student-proposed missions, solar neutron observations, for this radiation measurement (see Section 2.1). An image of the ChubuSat-2 satellite in orbit is shown in Fig. 1.

In this paper, we describe the mission concept and overall design of the ChubuSat-2 satellite, and report on design and development of the mission instrument, i.e. the radiation detector (RD).

2. ChubuSat-2 Satellite

2.1. Mission concept

There are two main missions for the ChubuSat-2 satellite. One is to observe neutrons and gamma-rays, mainly from the Earth, such as atmospheric neutrons and gamma-rays from thunder clouds in the same orbit (altitude 575 km, and incli-
nation angle 31 degrees) and at the same time as ASTRO-H, and to accumulate such background or noise data which are very useful for ASTRO-H X-ray and gamma-ray celestial observations. We will also explore the possibility of monitoring radiation disasters such as nuclear accidents from space.

Furthermore, we have added solar neutron observations to the radiation measurements. Solar neutrons were first observed in 1982, but there have only been about a few tens of successful detections so far. Neutrons are not affected by the magnetic field on the solar surface and in the interstellar medium unlike protons and electrons, and thus they reach the Earth with original information about acceleration on the solar surface maintained. They are considered to be direct probes to clarify the ion acceleration mechanisms. However, the currently working space detector, SEDA-AP FiBer detector (FIB), on the international space station (ISS), was suffered from the neutron background due to the ISS itself with a huge mass (~400 ton). The tiny ChubuSat-2 with a mass of 50 kg is expected to have a much smaller neutron background than SEDA-AP. Furthermore, neutron detectors in space can access energies lower than 100 MeV. Neutrons are attenuated by the Earth’s atmosphere (attenuation factor: 1/100000–1/100 depending on the altitude), so it is difficult to observe neutrons with an energy below 100 MeV on the ground.

We emphasize that this solar neutron observation project was originally proposed by graduate students at Nagoya University. Nagoya university has started a leadership development program for space exploration and research as a program for space exploration and research as a program for the leading graduate school (LGS), since FY 2012 after selection by Japan Society for the Promotion of Science (JSPS). This program aims to develop international leaders who can spur innovations that will expand the space utilization using collaboration with international amateur radio users. Details of the improvements are shown in table 1.

The system block diagram and specification are shown in Fig. 3 and table 2. The satellite consists of satellite bus instruments (attitude control and data processing system, power control system, communication system, structural and mechanical system, thermal control system, and harness between instruments) and one mission instrument. The data processing of both housekeeping (HK) data and mission data for the on-board instruments, attitude control, command processing, and satellite sequence control are managed by the on-board computer (OBC) alone. Electrical power is provided to each sub-system by the power control unit (PCU). The nominal power consumption is about 49 W including 12 W for the mission instrument.

The HK data for the spacecraft bus instrument and commands can be communicated in the amateur radio band (UHF and VHF). The RD mission data will be transferred via S-band with a transfer speed of 200 kbps to the ground station at Kyushu university in Japan during passes three times per day. The down-linked data size will be about 10 Mbytes per day.

3. Radiation Detector (RD)

3.1. Overall system

The radiation detector (RD) has been newly designed and developed by Nagoya University for the ChubuSat-2 satellite. It is composed of sensors which detect radiations and electronics which process the signals from the sensors. All the components are installed in one Aluminum box with a size of 15.2 cm×17.0 cm×18.5 cm (see lower panel of Fig. 4). The weight is approximately 6 kg and the total power consumption is about 12 W.
Fig. 2. The ChubuSat-2 satellite, viewed from two different angles. The satellite will be attached to the rocket interface via the separation part PAF 239M (bottom of Left panel).

Table 1. Improvements of ChubuSat-2 with respect to ChubuSat-1.

<table>
<thead>
<tr>
<th></th>
<th>ChubuSat-1</th>
<th>ChubuSat-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission instrument</td>
<td>optical and infrared cameras</td>
<td>radiation detector</td>
</tr>
<tr>
<td>Solar cells</td>
<td>attached to 3 sides</td>
<td>attached to all 6 sides</td>
</tr>
<tr>
<td>Secondary battery</td>
<td>Ni-MH (21/strings×5)</td>
<td>Ni-MH (18/strings×4)</td>
</tr>
<tr>
<td>Capacity (Ah)</td>
<td>9.5</td>
<td>14.8</td>
</tr>
<tr>
<td>Communication</td>
<td>amateur radio ×2</td>
<td>amateur radio ×2, S-band×1</td>
</tr>
</tbody>
</table>

The uniqueness of the RD compared with the other neutron instrument SEDA-AP FIB may be summarized by the following three points: 1) The RD can detect both neutrons and gamma-rays simultaneously, while FIB can observe only neutrons. 2) The RD has the same detection area with 100 cm² as SEDA-AP FIB, but is so compact and light that we can install on the micro-satellite. This was done by using the novel small photo-sensor Multi-Pixel Photon Counter (MPPC) instead of Photo-Multiplier Tubes (PMTs) as used in the SEDA-AP FIB. 3) The neutron backgrounds are expected to be low since the neutrons generated by the satellite itself can be negligibly small compared with the ISS.

3.2. Sensor

The RD sensors are composed of 100 multi-layered plastic scintillator bars each with size 1 cm × 1 cm × 10 cm and a GAGG (Ce: Gd₃Al₂Ga₃O₁₂) scintillator array with an area of 10 cm × 10 cm and a thickness of 1 cm (Fig. 4). The plas-
tic scintillator bars are surrounded with anti-coincidence plastic scintillators for rejecting charged particles. A scintillation light from each scintillator is read out with a novel silicon semiconductor device: Silicon Photomultiplier (or Multi Pixel Photon Counter (MPPC)) developed by Hamamatsu Photonics. It has a sensitive area of 6×6 mm and a quantum efficiency of 35% at 450 nm. It uses a very low bias voltage, 50–60 V, and can realize a high gain of 10^6 which is similar to that of a photomultiplier tube (PMT) with a high bias voltage (~1000 V). The GAGG scintillator and MPPC are very attractive devices with an excellent performance as radiation sensors, but have not been used in space yet. Hence, verification of the detector technology in orbit is also another purpose of this instrument.

The detection principles for neutrons and gamma-rays in the RD are as follows. A neutron interacts with hydrogen atoms in the plastic scintillator bars via elastic scattering. The recoil proton passes through some bars and loses its energy in each bar. The incident neutron energy in the 30–120 MeV range can be determined by following the proton track. The same detection technique has been used and verified in ground-based neutron telescopes,7) and SEDA-APF on the ISS.5) The RD is also sensitive to soft gamma-rays in the 200–1000 keV range with the Compton camera technique. A gamma-ray interacts with the plastic scintillator by Compton scattering, and a scattered photon is absorbed in the GAGG scintillator array. Using two interacting points in the plastic and GAGG, we can determine the incident energy of a gamma-ray and constrain its incident angle to an arc within ~10 degrees. By accumulating some photon events coming from the same direction, we can identify a gamma-ray source (this is the “Compton camera”). We can also use a photoelectric absorption event in the GAGG scintillator array after passing through plastic scintillators.

Table 3. Specifications of the radiation detector.

<table>
<thead>
<tr>
<th>Detector</th>
<th>100 plastic scintillator bars + GAGG (Ce) scintillator array read out with Multi Pixel Photon Counter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical Area</td>
<td>100 cm²</td>
</tr>
<tr>
<td>Energy Range</td>
<td>30–120 MeV (Neutrons) 200–1000 keV (Gamma-rays)</td>
</tr>
<tr>
<td>Detection Efficiency</td>
<td>1<del>2% (Neutrons) 1</del>2% (Gamma-rays)</td>
</tr>
<tr>
<td>Weight</td>
<td>6 kg</td>
</tr>
<tr>
<td>Size</td>
<td>15.2 cm × 17.0 cm × 18.5 cm</td>
</tr>
<tr>
<td>Nominal Power</td>
<td>12 W</td>
</tr>
<tr>
<td>Down-linked Data</td>
<td>~10 Mbyte per day</td>
</tr>
</tbody>
</table>

Fig. 4. Upper panel: Schematic of the radiation detector (RD). The size of the RD is 15.2 cm×17.0 cm×18.5 cm. It is mechanically connected to the satellite structural panel, and electrically connected via a D-sub 9pin connector to the on-board computer. Lower panel: Cross sectional view of the RD. The RD consists of mainly radiation sensors and readout boards.

Fig. 5. Detection principle of the RD. Neutrons can be detected in multi-layered plastic scintillators (shown by black), while gamma-rays can be detected in both plastic and GAGG scintillators via Compton scattering (shown by red). The anti-coincidence detectors (shown by orange) are used for rejection of charged particles such as protons and electrons.
3.3. Electronics

The schematic view of the signal processing electronics is shown in Fig. 6. Each plastic scintillator bar is read out with MPPCs at both sides to determine the incident position along the bar direction, and 2 MPPCs are attached to one anticoincidence detector. The GAGG 10×10 array is read out by MPPCs attached to each GAGG crystal. So there are in total 312 channels consisting of 200 from plastic bars, 12 from anti-detectors, and 100 from the GAGG crystal array. The MPPC signals are processed independently by analog and digital electronics boards located around or under the sensors. The charge charge from each MPPC is sent to an electrical board and converted into a voltage pulse in the fast charge-sensitive pre-amplifier, and after amplification, the pulse height (PH) is converted to a digital value by a 14-bit analog digital converter (ADC) with sample and hold function at the pulse peak timing. A high voltage $+54 \sim 55$ V is required for the MPPC operation, so the electronics board provides the bias voltage to each sensor. This voltage is controlled and adjusted by checking the sensor temperature automatically in a Field-Programmable Gate Array (FPGA).

When an event trigger occurs in any plastic scintillator bar or any GAGG crystal, the data acquisition will start. The event-by-event data with all the PHs from 312 channels are produced with a size of $\sim 600$ byte per event (2 bytes per channel). Since the original data size is relatively large and the down-linked data size is limited to about 10 Mbyte per day, the RD data will have to be compressed by the on-board FPGA. Anti-coincidence events are judged as charged particles, and have to be removed. In addition, we implemented several logics: 1) removal of the detector channels with a low PH value (so-called zero-suppression) and 2) reduction of the trigger rate by a factor of $1/n$ ($n=1,2,4,\ldots,128$) in the nominal data and change of the reduction rate during a solar flare. In this compression, the data size will be reduced by a factor of about 10, and compressed data are sent to the OBC and stored in the OBC on-board memory with a size of 1 Gbyte until the telemetry down-link starts. We also have a housekeeping (HK) data for monitoring the RD power status, high voltage values and temperatures, which are outputted at fixed time intervals to the OBC.

4. Current Status and Future

We have finished the preliminary design review (PDR) and JAXA safety review phase 0/1 on March, 2015. The configuration of the on-board instruments is almost fixed. The critical design review (CDR) and JAXA safety review phase 2 will be held on August 2015. The flight model (FM) will be integrated and tested on September 2015. The interface check with the rocket, separation shock, vibration test, and thermal vacuum test are planned soon after the FM fabrication. ChubuSat-2 will be launched with the ASTRO-H in the winter of FY 2015.

Fig. 7. Upper panel: Plastic scintillator bar with white reflector painted. The size of one bar is 1 cm × 1 cm × 10 cm. It is stacked to 10×10 layers for neutron detections. Lower panel: 5×5 GAGG (Ce) scintillator array. The array size is about 5 cm × 5 cm with a thickness of 1 cm.

We have developed a breadboard model (BBM) and a mechanical test model (MTM) of the RD, and performed a vibration test on both. The BBM of the GAGG scintillator array and plastic scintillator bar are shown in Fig. 7. The Qualification Test (QT) level: 18 Grms in the frequency range of 20–2000 Hz, was imposed on the BBM. Figure 8 shows a picture of the vibration test using the vibration facilities at Nagoya University. After verification of the BBM and MTM, the engineering model (EM) and flight model (FM) fabrication are now under way. Figure 9 shows the internal detector structure of the EM. A performance test using cosmic-ray muons in a laboratory and a proton beam at an acceleration facility, as well as thermal vacuum and vibration test at Nagoya university will be employed for the RD EM and the FM.

5. Conclusion

The ChubuSat-2 satellite developed by Nagoya university, Daido university, and MASTT was selected as one of the four piggyback payloads of the X-ray satellite ASTRO-H by JAXA last summer. The aim of this mission is 1) to support ASTRO-H
celestial observations by monitoring the radiation environment in the same orbit at the same time as ASTRO-H and 2) make the amateur radio transceiver available to world-wide amateur radio users for message communications. The mission instrument, radiation detector (RD) which can observe neutrons and gamma-rays simultaneously, is newly designed and developed by Nagoya university. The satellite and RD flight model are now under development. ChubuSat-2 will be launched with ASTRO-H in the winter season of FY 2015.

References