SPRITE-SAT: a Micro Satellite for Scientific Observation of Transient Luminous Events and Terrestrial Gamma-ray Flashes

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SPRITE-SAT is a micro satellite in the size of 50 cm cube and weighing 45-kg, designed and developed by Tohoku University. Its mission objective is to conduct scientific observation of atmospheric luminous emissions called "sprites" and terrestrial Gamma-ray flashes. Both are recently discovered phenomena and their mechanisms are still under the veil. SPRITE-SAT was developed to achieve significant observations to determine clear models of these mysterious phenomena. On January 23rd, 2009, SPRITE-SAT was successfully launched by JAXA's H-IIA rocket as a piggyback payload of Greenhouse Gas Observation Satellite (GOSAT). The spacecraft is now in a sun-synchronous polar orbit with 670 km altitude from the Earth's surface. This paper describes a general overview of the spacecraft and its mission.

Key Words: Micro Satellite, Sprites, Lightning, Transient Luminous Events, Terrestrial Gamma-Ray Flash

1. Introduction

SPRITE-SAT is an Earth science micro satellite designed and developed by the faculty and student members of Tohoku University, Japan. The objective is to monitor luminous emissions in the upper atmosphere, called "sprites"¹⁻³⁾ (see also Fig.1.)

Sprites are a type of Transient Luminous Events (TLEs) that occur in the middle atmosphere (typically 40-90 km altitude, from upper Stratosphere to Mesosphere). They are frequently observed associated with lightning discharges in the lower atmosphere. Upward lightning discharges into clear air have been reported by airplane pilots worldwide since the start of the early 20th century. However, the first visual evidence of a TLE phenomenon was documented in 1989. An image of an unusual luminous electrical discharge over a thunderstorm had been obtained with a high sensitivity video camera⁴⁾. Such optical signatures of these events were later named "sprites" and "elves," both of which come from fairies in fantasy. Today, various types of the luminous events are reported and catalogued⁵⁾ (see also Fig.2.)

Although extensive studies on sprites have been made since their first documentation, their characteristics and even the fundamental mechanisms cannot be fully explained so far.

Brief bursts of gamma-rays coming from outer space have been observed since the 1960s, but recent observations suggest

Fig. 1. Artist's view of SPRITE-SAT with the deployed gravity gradient boom.

That shorter bursts of gamma-rays occur in the Earth's atmosphere. Such bursts are called the Terrestrial Gamma-ray Flashes (TGFs). The flashes are considered generated by high-energy photons in the atmosphere and, therefore, a strong relationship is inferred with the thunderstorms and TLEs, such as sprites, as a possible source of these gamma-ray bursts.

Fig. 2. Various TLE types in the upper atmosphere.

Fig. 3. Piggyback payloads on the H-IIA upperstage.
(courtesy of JAXA)

Fig. 4. Instrument locations on SPRITE-SAT.

SPRITE-SAT was designed and developed to achieve significant observations of these natural events in the upper atmosphere from the orbit. Nadir observations of sprites are particularly essential to identify the horizontal structure of the sprites. Also concurrent measurements of lower lightning discharges, TLEs and TGFs from space are important to understand the relationship and generation mechanisms of

TLEs and TGFs.

Fig. 5. Arrangement of on-board instruments and sensors.

SPRITE-SAT was manufactured and integrated by faculty and student members in the Science and Engineering departments of Tohoku University, with technical supports from mentors (well-experienced experts). Students played leading roles in the assembling and testing processes. On January 23rd, 2009, the spacecraft was successfully launched as a piggyback payload of the H-IIA-15 rocket for the JAXA's Greenhouse Gas Observation Satellite (GOSAT). SPRITE-SAT is now in a sun-synchronous polar orbit with 670 km altitude from the Earth's surface. (see Fig.3.)

To provide useful information for microsatellite developers, this paper summarizes the system design, on-board sensors, and initial operation of SPRITE-SAT.

2. Spacecraft Design

2.1. System overview

The spacecraft structure is cubical with a side length of 50 cm. Its attitude stabilization is provided by a deployable gravity gradient boom which was newly developed for SPRITE-SAT²⁾. The nominal attitude of the spacecraft is oriented in such a way that the bottom panel of the satellite (-Z panel) is always directed toward Earth. During the de-tumbling phase, two single-axis magnetic torquers are used to slow down the rotational motion of the spacecraft in prior to the boom deployment and to damp the liberation motion after the deployment.

The overall specification of the spacecraft is listed in Table 1.

2.2. Onboard science instruments

As illustrated in Fig. 4 and Fig. 5, SPRITE-SAT equips with the following science instruments.

LSI-1 (Lightning Spectrum Imager-1):

The objective of the Lightning Spectrum Imager (LSI)-1 is to detect lightning flashes. The camera features a CMOS detector with a format of 512 x 512 pixels. Observations are being made in the spectral band of 740-782 nm. LSI-1 and LSI-2 have a square field of view (FOV) of 29° corresponding to a ground surface side length of 342 km.

LSI-2 (Lightning Spectrum Imager-2):

The objective of LSI-2 is to detect sprites. The camera features a CMOS detector with a format of 512 x 512 pixels. Observations are made in the spectral band at 762 nm. By subtracting simultaneous LSI-1 and LSI-2 images from each other, the image of sprites can be extracted from the background illumination of cloud-to-ground and inter-cloud lightning discharges.

WFC (Wide Field-of-view Camera):

This camera is being used to determine the location of lightning flash which is related to the TGF event. This high sensitivity panchromatic CCD camera has a fish-eye lens covering 140°.

TGC (Terrestrial Gamma-ray Counter):

Terrestrial Gamma-ray Counter (TGC) is provided by JAXA/ISAS and the University of Tokyo. With a FOV of 134° x 180°, it detects gamma-ray flashes caused by lightning discharges with a time resolution of 0.25 ms.

VLF receiver:

The gravity boom is also used as a very low frequency (VLF) antenna. The receiver electronics was developed by Stanford University. The objective of the VLF receiver is to measure the radio emissions from channels of lightning discharges not only of cloud-to-ground but also of intra-cloud discharges.

2.3. Attitude sensors and magnetic torquers

SPRITE-SAT has multiple attitude sensors and an active damping control system. The significant sensor for the control system is 3-axis magnetometers (termed as Geomagnetic Aspect Sensor, GAS). The GAS was integrated by Tohoku University using a commercial off-the-shelf three-axis magnetometer chip.

The measurement sensitivity is 1 V/gauss, and the output range is ± 2.5 gauss (2.5 V at 0 gauss). With an 8 bit AD converter, the GAS has the measurement range of magnetic field in ± 0.6 gauss (= 60,000 nT) with the resolution of 470nT.

In addition to GAS, the spacecraft equips Sun Aspect Sensor (SAS) using solar cells on 6 outer panels of the spacecraft, and micro electronics and mechanical systems (MEMS) gyros and accelerometers which were built in Tohoku-AAC MEMS Unit (TAMU) for off-line attitude determination.. The 3-axis orientation of the spacecraft in the inertial space is obtained by the combination of GAS and SAS, and the time history of the attitude profile will be determined in a good precision by using gyros and accelerometers with a Kalman filter process.

Furthermore, the spacecraft equips High-sensitivity Star Sensor (HSS), which is used as a star tracker in future. This sensor features a high sensitivity panchromatic CCD imager. Additional attitude information can be obtained by comparing the angle pattern of stars detected by the imager and that in a star-chart.

In order to provide active damping capability, a couple of coreless-type magnetic torquers (MTQ, see Fig. 6) were developed and attached on the side panel of the spacecraft in X and Z axes. The specifications of the torquers are listed in Table 2.

Table 1. The overall specification of SPRITE-SAT.

Spacecraft size	W 490 x D 490 x H 494 mm after mast deployment W 490 x D 490 x H 1354 mm
Spacecraft mass	45.3 kg
Attitude control	Type: gravity gradient stabilization Deployable boom: 860 mm in length, tip-mass: 3.680 kg, sleeves: 0.5 kg Sensors: 3-axis magnetometers in GAS (Geomagnetic Aspectmeter Unit) Actuators: 2-axis magnetic torquers (MTQ)
Attitude and orbit sensors	3-axis sun sensors (6 solar cells) 3-axis magnetometers (in GAS) 3-axis magnetometers, TAMU (Tohoku-AAC MEMS Unit) 3-axis gyro sensors (in TAMU) 3-axis accelerometers (in TAMU)
Power subsystem	Solar cells: P-type single crystalline silicon, 42 series/panel x 5 panels Batteries: 9-cell NiMH (total 3.3AH, 10.8V) Power generation: 23.5 W (avg. in 62-min sunshine per orbit) Power consumption: 22.0 W (observation mode), 12.0 W (communication mode), 9.5 W (at typical mode)
RF communications	Uplink: UHF, 1200 bit/s at Sendai station, Japan Downlink: S-band, 0.1 W, 9.6 or 1.2 kbit/s Primary data acquisition: Sendai station, Japan Secondary data acquisition: Kiruna station, Sweden

Table 2. Specification of magnetic torquers.

device name	MTQ_X	MTQ_Z
Position	side panel (-X)	bottom panel (-Z)
size (W x D x H)	315 x 315 x 10 mm	410 x 300 x 35 mm
Mass	420 g	668 g
num. of coil turn	62	11
core area	0.0652 m ²	0.1039 m ²
magnetic moment	0.22 Am ²	1.25 Am ²

Fig. 6. The flight model of MTQ-X (left) and MTQ-Z (right).

Fig. 7. Be-Cu ribbon spring (left) and the cross-section sketch of the mast mechanism.

2.4. Deployable mast

The deployable mast (MST), which has a 3.7 kg mass at the end tip and in the length of 180 mm in the stored configuration (including the tip mass), can be deployed up to 1000 mm. A ribbon spring made of Be-Cu is used to provide the extension force (see Fig. 7). Tapered thin aluminum tubes were arranged to cover the ribbon spring. These tubes work as an extendable telescope to increase the stiffness of the structure and ensure the electrical conductivity as a VLF antenna after the deployment. The whole mast structure is electrically isolated from the spacecraft main body using glass-reinforced epoxy plates.

The tip mass is locked by four latching hooks, which are closed and tightened by nylon cables during the launch. The nylon cables are cut out by a burning command (using a Ni-Cr heater) in orbit, then the hooks are opened, so that the telescopic mast extends into the final configuration. Some pictures of the flight model of the mast are shown in Fig. 8.

2.5. Attitude control

Onboard active damping control is conducted by a simple B-dot law using GAS and MTQ for the X and Z axes independently. A schematic timing chart is depicted in Fig. 9. Both MTQs are operated in a 4 second cycle such that they are active for 2 seconds after 2 seconds of interval, where the MTQ torques have only three states: positive maximum, zero, and negative maximum. GAS measurement is conducted for the period when the MTQs are inactive.

The control law is relatively simple. Let $b_x(t)$, $b_z(t)$ be the GAS measurement values in x and z axes at time t , and τ_x , τ_z be the three-state torque command to each MTQ. Then τ_w ($w = x$ or z) is by the following rule:

if $b_w(t) - b_w(t-4) > 0$ then $\tau_w = -1$ (negative maximum),
 if $b_w(t) - b_w(t-4) < 0$ then $\tau_w = +1$ (positive maximum),
 else $\tau_w = 0$

The control torque acting on the satellite can be simply computed by the following vector form equation:

$$N = M \times B,$$

where M is a torque vector generated by MTQ and B is a vector of the Earth's magnetic field

Fig. 8. Flight model of the deployable mast (A: before deploy, B: after deploy, C: hooks closed, D: hooks opened).

Fig. 9. A schematic time chart for the MTQ control.

2.6. Ground station

A ground station that equips a twin Yagi antenna for UHF uplink and a 2.4 mφ dish for S-band downlink was prepared in Tohoku University, see Fig. 10. Both antennas are mounted on a common remotely-controlled 2-axis gimbals table. Another downlink station with an S-band dish was prepared in Kiruna, Sweden to increase the amount of data transmission.

3. Initial Operation and Results

After the successful launch and orbital insertion, the SPRITE-SAT was successfully operated from the ground station in Tohoku University, up to the point of the on-board controller problem mentioned later. The tracking of the

satellite was based on the launch information of the rocket for the first few days, then has been done with the two-line elements (TLE) of the orbit. The international ID and catalog number of the SPRITE-SAT is 2009-002C 33494⁶⁾.

Fig. 10. UHF and S-band antennas on the roof of the science department building (left) and the operation room (right) in Tohoku University.

Initial attitude operation was also successfully conducted. At the beginning, the spacecraft was in a tumbling motion at about 4-5 deg/s in all 3 axes. By means of magnetic torquers, the motion went into a single axis rotation, then a slow-rate tumbling at about 0.2-0.3 deg/s. See Fig.11 for the time history of the spacecraft in orbit. Detailed results of the attitude determination and MTQ-based control are presented in another paper⁷⁾. The results of thermal system modeling and flight verification are also presented in ISTS 2009⁸⁾.

The gravity boom/VLF antenna was also successfully deployed on February 4th, 2009, after the attitude rate went down around 0.1 deg/s and waiting for an appropriate timing so that the +Z panel, the boom side, goes opposite to the Earth.

Fig. 11. History of the spin rate of SPRITE-SAT in orbit.

In the initial operation period, TAMU (Tohoku-AAC MEMS Unit) was successfully tested. TAMU includes multiple commercial-off-the-shelf components, including 8051 microcontrollers, 4 Mbit Magnetic RAM, and CAN-bus interface, and all these components worked normally in the orbital environment. Attitude measurement devices also worked well to record the de-tumbling and attitude damping sequence. The initial report was presented in an NASA workshop⁹⁾.

A test image of the WFC, a high-sensitivity CCD imager with a fish-eye lens, was taken almost 12 hours before the mast deployment. Fig. 12 shows a night view of the Earth around the East China Sea, in which the airglow is seen on the Earth's limb and the location of the artificial lights of major cities are identified.

On the other hand, the onboard main controller had a problem after the mast deployment, and the satellite has been out-of-control, even though its battery and power system are in a good condition. Scientific observation therefore has not yet started, as of June 1, 2009.

4. Conclusions

In this paper, the system design, on-board sensors, and initial operation of SPRITE-SAT were described. The mission of SPRITE-SAT was sharply focused on the observation of transient luminous events and terrestrial Gamma-ray flashes. The spacecraft was developed just within 15 months from selected as a piggy-back payload to the launch-site delivery. The development cost was also remarkably small comparing to other spacecraft.

Technological verification of the on-board bus systems was successfully conducted after the launch, while scientific observation is still awaited.

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Fig. 12. A test image of night globe taken by WFC: Local Time = 2009/02/04 00:51:39 JST, Longitude = 128.972675 E (deg), Latitude = 33.397187 N (deg), Altitude = 667.994 (km).