OVERVIEW OF ARC EVENT GENERATOR AND INVESTIGATION SATELLITE HORYU-IV

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ABSTRACT

HORYU-IV is a 30cm cubic satellite with an approximate mass of 10kg. HORYU-IV carries a high voltage photovoltaic solar array capable of generating a voltage up to 350V. Its main mission is to acquire an arc current waveform by an onboard oscilloscope and capture its image by a camera triggered by the oscilloscope. In addition, it plans to carry out various scientific experiments. The satellite was successfully launched to an orbit of 575km altitude and 31^{o} inclination on February 17, 2016 by H-IIA rocket as a piggyback satellite with ASTRO-H (Hitomi) satellite. Overview of the satellite and its mission are presented.

1. INTRODUCTION

HORYU-IV (Arc Event Generator and Investigation Satellite, AEGIS) satellite is part of the HORYU series, nano-satellites developed at Kyushu Institute of Technology (Kyutech) since 2006. HORYU-IV will be the second satellite of the series to be, after HORYU-II launch on May 18, 2012. HORYU-II development and achievements were reported by Refs.[1-9].

HORYU project aims at developing at a low cost and in a short time, a reliable technology demonstration satellite that will contribute to the advancement of space science and technology, and HORYU-IV mission statement is to acquire on orbit data of discharge phenomena occurring on high voltage solar array to deepen understanding of satellite charging, to contribute to the reliability improvement of current space systems, and to positively contribute to the realization of future high power space systems.

Electro-static discharge (ESD) phenomenon occurs mainly on solar array panels and can cause partial or even complete satellite power loss, which often results in the inability to perform the missions and ultimately in the satellite loss. From 1997 to the middle of 2000s, ESD on power system, such as solar array, solar array paddle drive motor, and power harness, was the major failure cause of satellites, especially for high power GEO telecommunication satellites that adopted 100V bus [10] to answer the demand of higher power usage due to proliferation of satellite broadcasting.

As a result of international collaborative efforts to improve the reliability of satellite solar panel and power system, ISO-11221, "Space systems — Space solar panels — Spacecraft charging induced electrostatic discharge test methods" was published in August 1st, 2011. Although the testing methods were developed with the best knowledge of what happens in space, there is nobody who saw where a discharge occurs on a solar panel nor its discharge waveform. No tests were ever carried out in space to make sure that what is observed in laboratory is actually the same as what is happening in space.

The first motivation of HORYU-IV project is the desire to answer questions such as: what are the effects of the difference between the plasma and vacuum parameters in chamber vs. space? does chamber walls influence results? has satellite motion a critical role in the observed results?. These questions need to be answered before confirming or disconfirming the theory and ground based observations the standard is based on. The results obtained by the HORYU-IV project will be reflected to the revision process of ISO-11221[11].

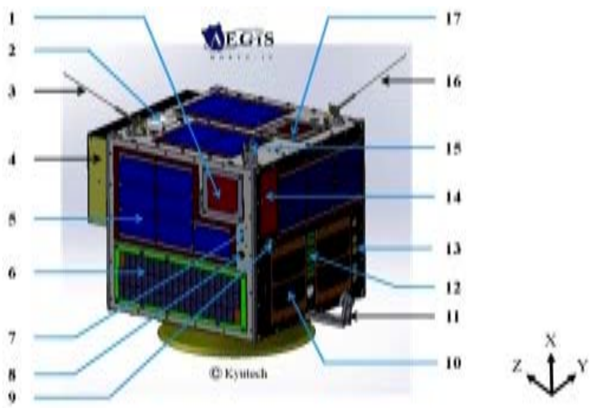
The second motivation is the aspiration to actively contribute to the development of the next generation high power space systems by providing a safe and reliable way of generating high photovoltaic power. In 2020's, the International Space Station plans on retiring, and future projects such as planetary exploration, space solar power systems, and space hotels are considered. These systems require high power, 1MW in the near future, and if their bus voltage stays at a safe level of about 100V, their weight will be tremendously high, whereas if bus voltage could be safely raised to 300V, future high power space systems mass could be reduced of nearly 20% as shown by Brophy et al. [12].

HORYU-IV project started on May 2013 after securing funding from Japan Society for Promotion of Science (JSPS). It was selected as a HII-A piggy-back payload with Astro-H ("Hitomi") in July 2014. From May 2013 to February 2016, 46 people from 18 countries were engaged in the satellite development. They were staffs and graduate students of Kyushu Institute of Technology. This international diversity was due to participation of graduate students who belonged to Space Engineering International Course (SEIC), Kyushu Institute of Technology. SEIC is a postgraduate curriculum to teach space engineering in English. The students are composed of Japanese and foreign students. Most of foreign students come from non-space faring countries, such as South East Asia, Africa, Latin America, and Eastern Europe.

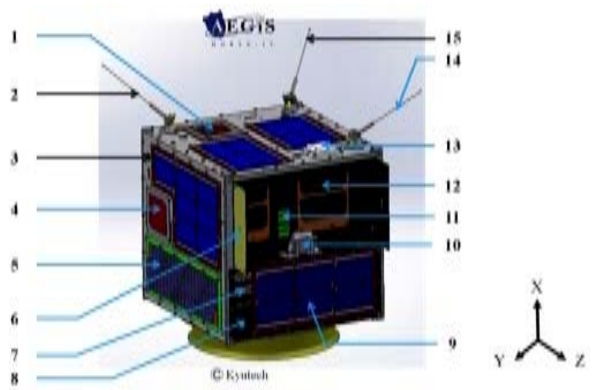
The total program duration is five years including two years of operation. The total program cost including operation is approximately 1.5 million USD, which is 7 times more than HORYU-II. HORYU-IV was successfully launched to an orbit of 575km altitude and 31^{o} inclination on February 17, 2016 (JST) by H-IIA rocket F30. The purpose of the present paper is to give overview of the satellite. Detail design and results of the main mission, discharge current waveform and image capture, will be presented in a separate paper [13].

2. SATELLITE DESCRIPTION

AEGIS is a cubic shaped nano-satellite (or lean satellite), which external envelope is 450(mm)x420(mm)x430(mm) with an approximate total mass of 10kg. The UHF antennas, the VHF antenna, and the arm holding the mirror are fixed, which makes AEGIS a deployment-free nano-satellite. Figure 1 shows how payload and bus are accommodated, and sections 2.1 and 2.2 give further details on the satellite bus and payload, respectively.



1. L-band antenna
2. GPS antenna (AODS)
3. UHF antenna
4. Langmuir probe (DLP)
5. Bus solar array (EPS)
6. High voltage solar array (HVSA)
7. Sun sensor (AODS)
8. Earth observation camera (CAM)
9. Vacuum arc thruster (VAT)
10. Discharge experiment solar array (DEG)
11. Mirror (AVC)
12. Secret ink (INK)
13. Photo-electron current measurement (PEC)
14. Electron collector (HVSA)
15. VHF antenna
16. UHF antenna
17. S-band antenna [14,15]



1. S-band antenna
2. UHF antenna
3. Earth observation camera (CAM)
4. L-band antenna
5. High voltage solar array (HVSA)
6. Langmuir probe (DLP)
7. External connector
8. Sun sensor (AODS)
9. Bus solar array (EPS)
10. Arc vision camera (AVC)
11. Secret ink (INK)
12. Discharge experiment solar array (DEG)
13. GPS antenna (AODS)
14. UHF antenna
15. VHF antenna

Figure 1 AEGIS external configuration

2.1. Bus

AEGIS bus is based on HORYU-II bus, and lessons learned from HORYU-II failures were implemented especially with regard to single event latch-up[3,9]. The three main differences between AEGIS and HORYU-II bus can be found in the on-board computer (OBC), communication (COM), and attitude and orbit determination sub-systems (AODS).

OBC integrated three microcontrollers: two H8 that watch each other and one PIC. Power reset of the H8 occurs every 24 hours independently of anomaly occurrence. In case of H8 malfunction, the PIC can reset the satellite through commands sent from the ground station.

For COM, in addition to UHF/VHF antennas, AEGIS also uses S-band patch antenna for transmission and L-band patch antenna for reception. Mission data (MD) and off-time housekeeping (OTHK) data are sent at a frequency of 2400.3MHz (amateur frequency of S-band spectrum) and speed of 100kbps. In case of S-band malfunction, MD and OTHK data will be sent through UHF antenna a frequency of 437.375MHz and speed of 1200bps. Beacon and real time housekeeping (RTHK) data, that give information on satellite status, are sent through the UHF antenna at a frequency of 437.375MHz and a speed of 20wpm and 1200bps, respectively. Commands will be received on the VHF antenna at frequency of 145-146MHz and speed of 1200bps. L-band is used to send a reset signal to the PIC in case of OBC malfunction using dual-tone multi-frequency (DTMF).

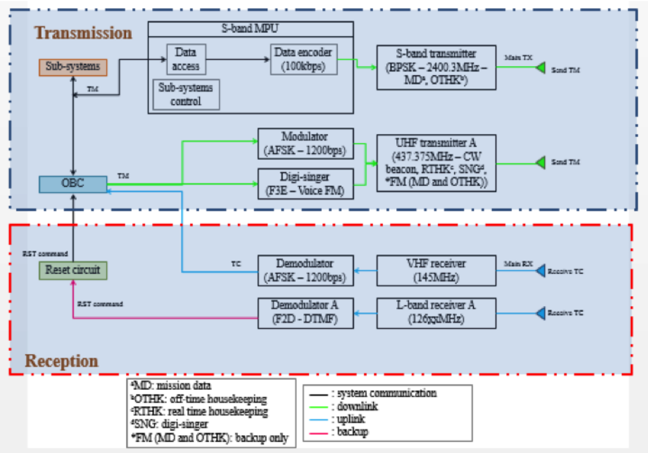


Figure 2 AEGIS communication block diagram

As for HORYU-II, AEGIS uses a permanent magnet and hysteresis damper for passive attitude and orbit control. The novelty for AEGIS is in the attitude and orbit determination, for which it uses six sun sensors and a GPS in addition of two three-axis control gyro-sensors.

Table 1 compares HORYU-II and AEGIS bus characteristics. Some aspects of the satellite bus system testing can be found in Refs.[16-19].

Table 1 HORYU-II and HORYU-IV bus characteristics comparison

HORYU-II	**HORYU-IV (AEGIS)**
Dimensions (X×Y×Z) [mm]	
350×310×315	450x420x430
Mass [kg]	
7.1	10
Orbit	
• Sun-synchronous sub-recurrent orbit • Altitude: approx. 670km	• Orbit inclination: 31° • Altitude: 575km
Downlink	
• UHF (437.375MHz) CW beacon (20wpm) • UHF (437.375MHz) FM 1200bps for data	• UHF (437.375MHz), CW, beacon (20wpm) • UHF (437.375MHz), FM, 1200bps for data • S-band (2400.3MHz), 100kbps for data
Uplink	
• VHF (145-146MHz)	• VHF (145-146MHz) • L-band (1.26GHz)
Solar array power	
• Max 4.5W • Average 2.6W (measured in orbit)	• Max.: 9W • Average: 5.2W
Battery	
• Ni-MH • 3 parallel, 3 series	• Ni-MH • 3 parallel, 6 series (5700 mAh at 7.2V)
Power consumption	
• Nominal: 0.7W • Peak: 3.3W	• Nominal: 5.1W • Peak (all missions ON): 15.3W
Attitude control	
• Passive control by permanent magnet and hysteresis damper	• Same as HORYU-II
Attitude sensors	
• Gyro sensor	• Gyro sensor • Sun sensor
Orbit determination sensor	
• None	• GPS
Deployment	
• UHF/VHF antenna	• None
Thermal control	
• Passive + battery heater	• Passive + battery heater
OBC	
• Renesas H8 HD64F36057FZV ×2	• Renesas H8 HD64F36057FZJV×2 • PIC 16F876A for power reset

2.2. Payload

AEGIS main mission is to acquire electro-static discharge (ESD) current waveform and picture, namely DIS. To achieve these objectives, oscilloscope (OBO) and camera (AVC) systems are developed in house. OBO is a four-channel oscilloscope with maximum 10MHz input bandwidth and 40MSa/s. OBO can be activated either by triggering itself or receiving an external trigger from HVSA subsystem. AVC is made of two 8bit B/W CMOS image sensor (752x480 pixels) video cameras. Each camera is attached to ±Z panel of the satellite as shown in Fig.1. The camera at –Z panel captures the image reflected on the mirror attached to the extended boom. The camera at +Z panel captures the image inside the hood that blocked the stray light as much as possible. The both cameras capture 2.8 video frames. Once it is triggered by the signal from OBO, it stores the video frames before and after the trigger signal so that successive images with/without arc event can be captured. Details of OBO and AVC can be found in Refs.[13,20].

Before the launch, the both instruments were tested extensively placing the satellite test model in a vacuum chamber where a LEO-like plasma was generated and the solar arrays were biased by illuminating HVSA by a halogen lamp from outside the chamber. Ref. [13] describes the detail of the first data obtained in orbit on February 24, 2016.

For the main mission to be executed, the generation of high voltage to induce discharges is essential. This is the role of the high voltage solar array (HVSA) mission. HVSA uses spherical solar cell arrays with a V_{oc} of 7.3V and I_{sc} of 2.3mA. Two panels of 58 arrays are mounted on AEGIS to allow the generation of 300V. HVSA mission was successfully executed and demonstrated on board HORYU-II with the generation of 350V (Figure 3). Development of high voltage generation technology and its application on board HORYU-II were well-described by Yoke et al.[4], and Iwai et al. [8]. Fukuda et al. [21] describes the aspect specific to HORYU-IV. In addition to study ESDs when they occur, another purpose of AEGIS is to study efficient methods of mitigating ESDs; this is the DEG mission. DEG mission investigates two types of mitigation techniques. One is film-based[22], and the other one is coating based [6]. Discharges are induced on triple junctions solar cells. Two sets of cells are covered with ETFE film (fTJA) whereas one set is coated (cTJA). On the satellite ±Z panels, a reference array (TJA) without any mitigation applied is mounted along with the film array. Data from these sets are compared to determine each method mitigation efficiency.

DEG was flown on HORYU-II, and AEGIS will serve as a platform to obtain more data and verify the previous results obtained. One difference from HORYU-II is that open-circuit voltage of TJA can be measured to investigate degradation of solar cell performance due to repeated discharges. Another difference is that AEGIS carries a double Langmuir probe making it possible to know the plasma density during the experiment.

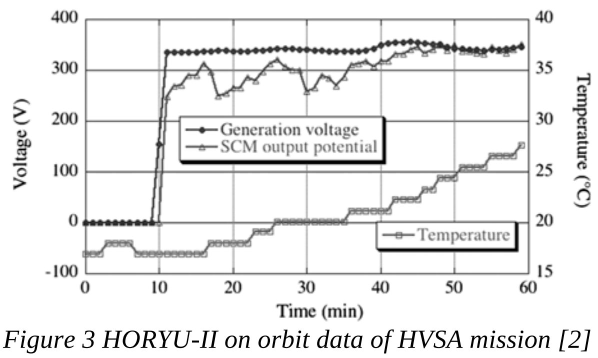


Figure 3 HORYU-II on orbit data of HVSA mission [2]

Along with DIS, HVSA, and DEG, there are seven missions, whose objectives are summarized in Table 2.

Table 2 AEGIS missions objectives

Mission	Objectives
Double Langmuir probe (DLP)	Measure plasma density and temperature. Use high voltage solar array to clean the probe surface by in-situ ion sputtering [23]
Vacuum arc thruster (VAT)	On-orbit demonstration of a trigger-less vacuum arc thruster, which circuit is directly connected to the high voltage solar array [24,25]
Secret ink (INK)	Study of surface degradation due to space environment exposure [26]
Photo-electron current measurement (PEC)	On-orbit measurement of photo-electron current [27]
Earth photography (CAM)	Photography the Earth using a CMOS camera module and distribute the pictures for space education awareness
Digi-singer (SNG)	Singing satellite. Upload songs from ground, use the vocal synthesizer on board the satellite and send back the song from AEGIS to the ground using UHF for space education purpose [28]. World premiere

3. PRELIMINARY FLIGHT RESULTS

HORYU-IV was launched aboard HII-A F30 at 17:45, February 17, 2016 (JST) from Tanegashima Space Centre. The satellite was inserted into an orbit of 575km altitude and 31° inclination from the rocket at 18:17:34. Figure 4 shows a video frame taken by the rocket second stage. From the video, we can see that the satellite was rotating around Y axis with 15 deg/s. After 22 days, when we turned on gyro sensors, we found that the rotation speed decreased to 10 deg/s.

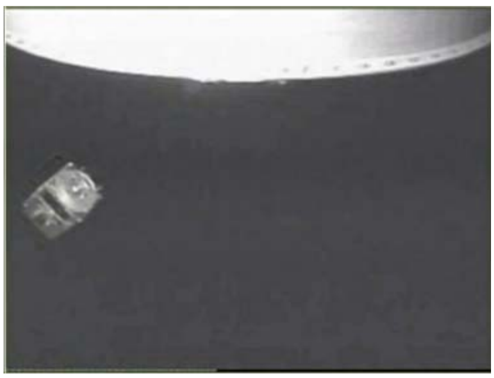


Figure 4 HORYU-IV after separation. The video taken from the HII-A second stage (from JAXA digital archive)

At 19:27, the Kyutech ground station received the first beacon signal from the satellite and confirmed the satellite is healthy. For the first one week, the satellite health condition was monitored. On February 24 (day 8), the OBO/AVC/HVSA missions started. Figures 5 and 6 show the housekeeping telemetry data obtained for the first two weeks. The spike in board temperature at 180 hours in Fig.5 is due to the operation of OBO and AVC boards. As of now, although the satellite OBC experience irregular resets frequently, the satellite keeps operating.

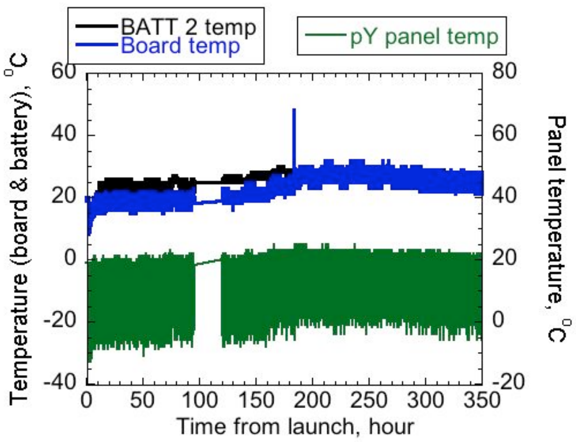


Figure 5 HORYU-IV temperature for the first two weeks

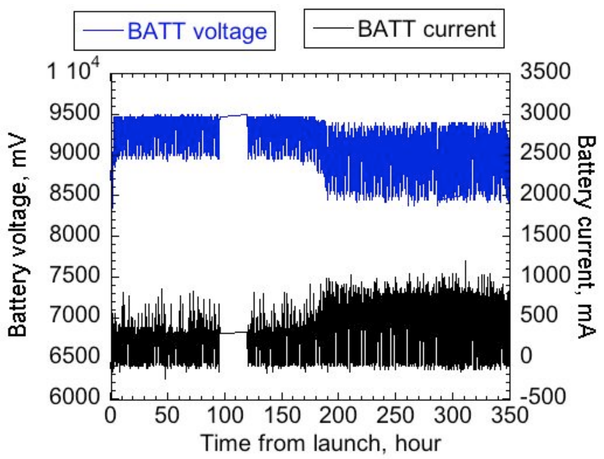


Figure 6 HORYU-IV battery condition for the first two weeks

4. CONCLUSION

HORYU-IV (Arc Event Generator and Investigation Satellite, AEGIS) aims at expanding state-of-art knowledge of electrostatic discharge in space. It successfully captured the discharge current waveform and the flash image on high voltage solar array in orbit for the first time in the world. The satellite intends to do various other ESD related experiments, such as discharge mitigation technology and solar cell degradation due to discharges.

There are other high voltage related missions, such as cleaning of Langmuir probe via ion sputtering and demonstration of vacuum arc thruster. Space environment related missions such as polymer degradation and photo-electron current measurement. The satellite will be also used for outreach purpose such as distribution of the Earth images and exchange of music.

As of April 3, 2016, we finished the initial experiment of OBO/AVC/HVSA and SNG missions. Although the experiments were successful, we still need to conduct many more experiments. Also there are other missions that wait to be executed. Once they are finished, the results will be shared among the community.

5. ACKNOWLEDGEMENT

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