ARICA: Demonstration of a Real-time Gamma-Ray Bursts Alert System using the Commercial Satellite Networks

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ABSTRACT

We demonstrate the real-time alert system of the transient astronomical sources such as cosmic gamma-ray bursts (GRBs) using two commercial satellite network devices. One is the Iridium's Short Burst Data (SBD) and the other is the Globalstar's STX-3. Although these satellite communication devices have been used in the space environment, it still needs to verify whether the network can be used as a GRB alert system. We are currently developing a 1U CubeSat called AGU Remote Innovative CubeSat Alert system (ARICA) which contains both SBD and STX-3 to demonstrate the real-time GRB alert system. The ARICA has been selected as the JAXA Innovative Satellite Technology Demonstration-2 and scheduled to be launched in the Japanese fiscal year 2021.

INTRODUCTION

Gamma-ray bursts (GRBs) are extremely energetic explosions that have been observed in distant galaxies and the brightest electromagnetic events known to occur in the universe. The long GRBs which have a duration of longer than two seconds are thought to be the emission from a relativistic jet produced by the death of a massive star colliding into a neutron star or a black hole. A subclass of GRBs, called short GRBs with a duration of fewer than two seconds, appears to originate from the merger of binary neutron stars or a neutron star and a black hole binary. The recent observation suggests a short GRB is the electromagnetic counterpart of a gravitational wave source (1).

GRBs have two characteristics. First, the duration of the prompt gamma-ray emission of a GRB is very short. It only lasts for a few milliseconds to a few minutes. On the other hand, the afterglow emission follows for a day to a week between an X-ray to a radio band. Second, GRBs are not possible to predict when and where they occur. Therefore, the observations of GRBs require a quick alert to the ground for the follow-up observations of afterglows by various telescopes to understand the nature of GRBs. There are two successful examples of the alert systems applied by *HETE-II* and *Swift*. These satellites made the breakthroughs in GRB observations thanks to the alert system.

High Energy Transient Explorer-II (*HETE-II*) was developed by the United States, France, and Japan and was launched in 2000 as the first dedicated satellite for studying GRBs. When *HETE-II* detects a GRB, it sends the detection data to the 15 ground stations installed along the equator (the inclination angle of *HETE-II* is 2°). The data are transmitted to the ground observer within seconds (2). This alert system enabled us to identify GRBs in real-time and distribute the GRB coordinates to ground observers within minutes (3). This feature had led to the discovery of the GRB association with a type Ibc supernova (4).

Swift is the GRB observation satellite developed by NASA and launched in 2004. *Swift* is a fully self-contained satellite that can automatically perform everything from a detection of a GRB to a maneuver of the spacecraft and follow-up observations by the onboard telescopes. The *Swift* uses the data relay satellite system called Tracking and Data Relay Satellite System (TDRSS) developed by NASA to provide the detection alert of GRBs to the ground in a few seconds. Thanks to its fast and accurate alert, *Swift* has been revolutionizing our understanding of GRBs such as detections of high redshift GRBs (5) and discovery of afterglow from a short GRB. (6)

Like these examples, the alert systems are playing a crucial rule in the study of GRBs. However, both

systems are difficult for a small project to introduce because of the permission to use for a non-NASA project in the case of TDRSS and the manpower to install many ground stations in the case of *HETE-II.* To overcome this situation, we propose the new GRB alert system using commercial satellite network services.

ARICA

The AGU Remote Innovative CubeSat Alert system (ARICA) is the 1U CubeSat mission to demonstrate the alert system of astronomical transient sources such as GRBs using currently available commercial satellite network services.

Demonstrate the commercial satellite network as a GRB alert system

We focus on the two commercial satellite networks taking into account the cost and the real-time communication capacity as a new GRB alert system. The networks in focus are the Iridium Satellite Communications and Globalstar Inc. The devices are Short Burst Data (SBD) for the Iridium network and STX-3 for the Globalstar network. The devices have been operated in the space environment in the past missions. However, the devices have not been fully tested as an alert system which requires a stable real-time communication between ground and space. The commercial satellite networks have great potential as the alert system of a transient astrophysical source for a small project with limited funding and human resource.

Iridium Satellite Network

The Iridium communication service which is consisted of 66 satellites on the Low-Earth Orbit (LEO) at 780 km altitude enables worldwide duplex voice and data communication. The telemeter and command data of SBD are transmitted and received through the internet, the ground station, and the satellites (Fig.1). The user only requires a computer to send (or receive) the data to (or from) SBD. In the ARICA mission, we introduce the SBD9603N (Fig.5) for both downlinks the data and uplink the commands. The global coverage of the Iridium satellite constellation provides highly reliable communications from pole to pole.

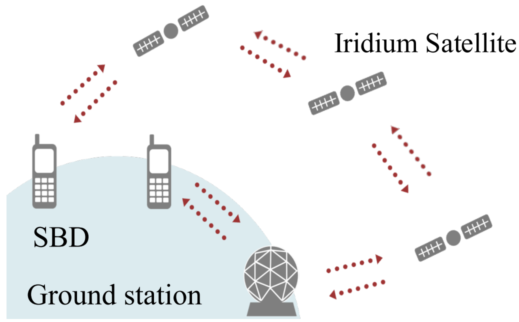

Figure 1: Iridium Satellite Communication

Globalstar Satellite Network

The Globalstar network is also designed to provide a simplex and a duplex voice and data system to the users. The 2nd generation constellation consists of 24 LEO satellites at 1414 km altitude. The data from Globalstar's device are received by one or more Globalstar satellites and immediately send to the 24 ground stations around the world (Fig.2). ARICA uses the STX-3 simplex modem to transmit the data to the ground (Fig.7).

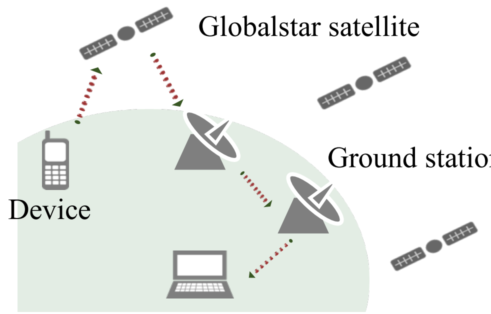

Figure 2: Globalstar Satellite Communication

THE ARICA INSTRUMENTS

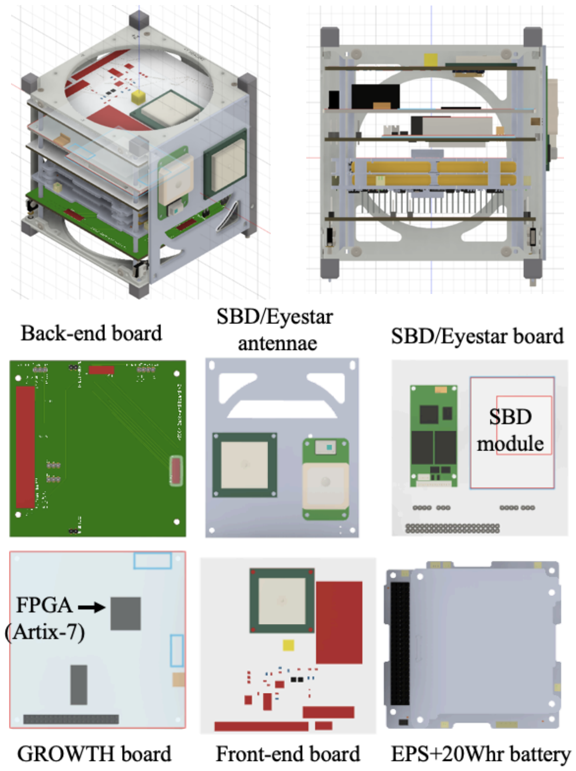

Figure 3: CAD images for ARICA components

ARICA consists of five boards inside and six panels (Fig.3). The front-end board has a gamma-ray detector and a GPS module. The GROWTH board (Shimafuji Electric Inc.), which contains an FPGA (e.g., processes the data of the gamma-ray detector), the GPS module, and EPS. It also handles the uplinked command from SBD. The Back-end board has a gyro sensor, connector to overwrite an FPGA code, and connectors of the remove-before-flight (RBF) switches. The SBD and EyeStar-S3 are installed on the SBD/Eyestar board. Eyestar-S3 is the flight Globalstar's STX-3 transmitter module developed by NearSpace Launch Inc.

The top side is exposed to space. Three sides and the bottom side are attached with solar arrays panels. One side contains the communication interface for the ground testing, antennae of SBD and Eyestar-S3, and the RBF pins.

The EPS/battery, solar arrays, and the 1U CubeSat structure are the flight products of AAC-Clyde Space Inc. The schematic diagram of all systems in ARICA is given by Fig.4.

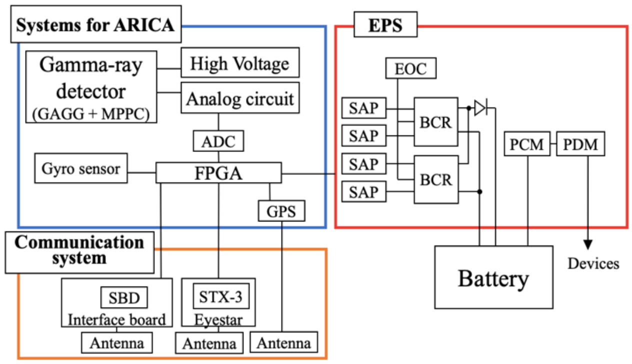

Figure 4: The schematic diagram of ARICA

The measured weight and power consumption of each component are shown in Table 1.

Table 1: Power and mass of components

Component	Mass (g)	Power (W)
Front-end board	42	3.6
GROWTH board	61	
Back-end board	28	< 0.1
SBD module + antenna	41	0.8
Eyestar-S3 + antenna	40	1.6
SBD/Eyestar board	27	< 0.1
GPS + antenna	21	0.2
CS 1U structure	136	
CS EPS battery	275	0.2
CS Solar arrays panel (x3)	42 (126)	
Detector (MPPC/GAGG/HV)	6	Included in the front-end and GROWTH board value.
Total	803	6.4

COMMUNICATION SYSTEM

SBD device features

We used SBD9603N as the device of the Iridium (Fig.5). The interface board (19603-IF-01-TL; Embedded Technology Corp.) consists of the electrical interfaces, a serial-data interface, DC power input, network available output, and a power on/off control line and RF connector (U. FL connector). The message to or from SBD is transferred as an e-mail attachment by the user. Therefore, we can get the data of ARICA and send the commands to ARICA only using a simple email system. The frequency range of SBD is 1616 MHz to 1626.5 MHz. The maximum downlink data size

is 340 bytes. The uplink data size is 270 bytes. The supply voltage is 5V and the allowed temperature range is -25^{o}C to 70^{o}C. The patch antenna MPA-D254-1621 (Maxtena Inc.) is used in the flight configuration.

Figure 5: Short Burst Data 9603N

SBD performance evaluation

We performed a ground testing of the SBD with the configuration consisted of the FPGA test board (Nexys4; Xilinx Inc.), GPS (GARMIN Inc.), SBD, and the antenna (Fig.6). We sent the GPS data through SBD every minute to an hour cadence. The rate of the success was 97%, and the average delay time, which is the time between the command execution and receiving the email message, was 12 seconds.

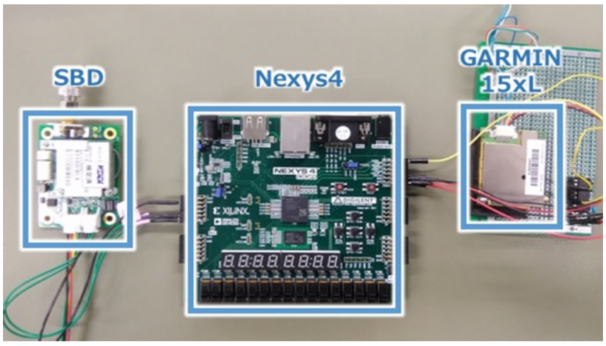

Figure 6: The setup of the SBD ground testing

Globalstar STX-3 device features

The STX-3 (Fig.7) is a simplex (transmit-only) satellite transmitter designed to send small packets of user-defined data to the Globalstar LEO satellite network. ARICA uses the STX-3 simplex modem because it covers a wide area in low power and small size with a simple TTL digital interface.

Figure 7: STX-3 on Eyestar-S3

The Eyestar-S3 (Fig.8) simplex module (NearSpace Launch Inc.) is used as the interface module of STX-3. By using this module, we can easily obtain the data from the NearSpace Launch (NSL) server.

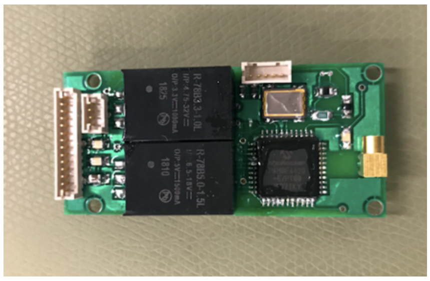

Figure 8: Eyestar-S3

The Eyestar-S3 has two transmit modes. In beacon mode, the Eyestar-S3 transmits set packet types for health and safety information with fixed formats at specified time intervals. This happens autonomously and requires no serial input or command to occur. In serial mode, Eyestar-S3 can be commanded to transmit any serial data that is sent to it, as long as the unit is available and not currently transmitting. Eyestar-S3 includes a flight processor interface, a patch antenna, four digital, and six analog inputs and a serial port. The Eyestar-S3 physical specifications are given in Table 2.

STX-3 performance evaluation

The ground demonstration of the Eyestar-S3 performed in a similar configuration to SBD. The success rates of the beacon and serial communication were 36% and 8%. According to NSL, if the success rate on the ground is 20%, it means the success rate in space can be close to 90% because of the less sensitive antenna in the ground environment. The delay time between sending command and getting the message via the NSL server was 7 sec on average. Fig.9 shows the schematic diagram of the ground testing.

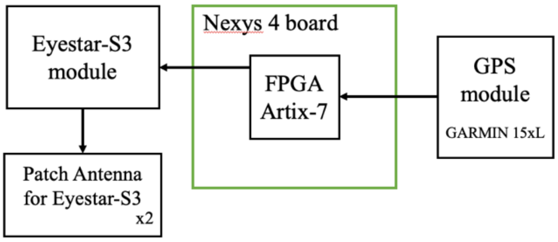

Figure 9: The schematic diagram of Eyestar-S3 demonstration

Table 2: Devices features

	SBD9603N (Iridium Communications Inc.)	**STX-3 (Globalstar Inc.)**
Dimensions	32 x 30 x 8 mm	29 x 21 x 4 mm
Weight	11 g	17 g
SBD interface board I9603-IF-01 (Embedded Technology Inc.)		
Dimensions		60 x 45 mm
Weight		20 g
Temperature		-40 to 60 °C
Maxtena patch antenna MPA-D254-1621 (Maxtena Inc.)		
Dimensions		45 x 45 x 6 mm
Weight		13 g
Temperature		-40 to 85 °C
Eyestar-S3 (NearSpapce Launch Inc.)	**Simplex module**	**Patch antenna**
Dimensions	55 x 26 x 15 mm	44 x 25 x 6 mm
Weight	22 g	15 g
Temperature	-30 to 60 °C	-30 to 60 °C

GPS module

ARICA employed the HT-GPS200.20 GNSS receiver (Hyperion Technologies B.V.) as a GPS device (Fig.10). It is a low mass (3g), low power (<150mW) GNSS receiver for the use in small satellites and is designed specifically for use in CubeSat platforms. This device offers a multi-constellation output, and the standard version is delivered with a TTL UART output. The antenna is AP.35A active patch antenna (35 x 35 x 5.5 mm) of Taoglas Inc. The dimensions of the GPS module are 20 x 15 x 3 mm, and the allowed temperature range is -40 to 85 °C.

Figure 10: HT-GPS200.20 GNSS Receiver

STRUCTURES

AAC Clyde Space 1U CubeSat Structure

We introduce a 1U structure (Fig.11) of AAC-Clyde Space Inc. in ARICA. This structure has a total mass of 0.156 kg and dimensions of 100 x 100 x 113.5 mm. The structure range is designed in such a way as to allow the stack of printed circuit boards to be mounted directly onto a set of four titanium rods housed in the structure endplates. The positions of four rods match with stacking the boards of the PC/104 standard.

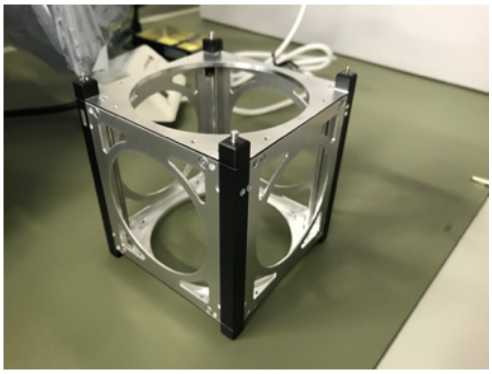

Figure 11: 1U CS structure

GAMMA-RAY DETECTOR SYSTEM

MPPC

Multi Pixel Photon Counter (MPPC) is a device called SiPM, which is a multi-pixel Geiger-mode Avalanche Photodiode (APD) photon counting device. This device is small and operates at low voltage comparatively (~50V). This feature is suitable for our mission because a low power and a small volume are required. The 6 mm squared MPPC is used for the flight (S13360-6050CS, Hamamatsu Photonics Inc.).

GAGG

Gadolinium Aluminium Gallium Garnet (Ce) (GAGG(Ce)) crystals have the advantage that they emit large amounts of light even in small crystals. They have a good sensitivity in the hard X-ray band (Table 3). In addition, it has been rarely used in space. Although BGO (Bi4Ge3O12) and NaI crystals are often used as gamma-ray detectors in space, GAGG crystals emit large amount of photons comparing to those of BGO and NaI (Table 3). The wavelength also matches nicely to our MPPC. GAGG crystal in ARICA is a 6mm cube and produced by EPIC Crystal Co., Ltd.

Table 3: Amount of lights for GAGG, BGO, NaI

	GAGG	BGO	NaI
Amount of lights (photons/MeV)	50,000	8,000	45,000
Emission wavelength (nm)	540	480	415

Assembling the gamma-ray detector

We developed the gamma-ray detector composed by MPPC and GAGG. In order to evaluate the performance, we tested using the Front-end board, the GROWTH board and Raspberry pi3 (Fig.12). This Front-end board includes the sensor of MPPC and GAGG, the high voltage module (HV: AiT HV80B A-1916) and an amplifier. The GROWTH board has 12 bits Analogue Digital Converter (ADC). The output analog signal from the amplifier inputs to the ADC on the GROWTH board. The digitalized signal is processed on the FPGA. We use Raspberry pi3 to send commands to the GROWTH board and save the data. The result shows that the energy resolution of ^{22}Na (511keV) is 7.4% ±1.3% (Fig.13). The linearity is also acceptable level in the ARICA mission (Fig.14).

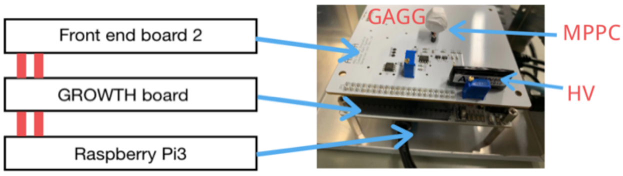

Figure 12: The setup for demonstration of the gamma-ray detector component of ARICA

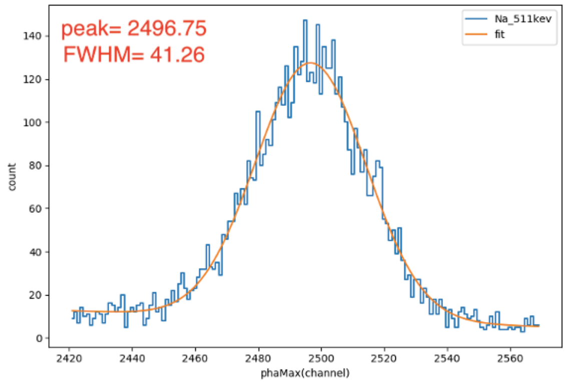

Figure 13: The spectrum of ^{22}Na (511 keV)

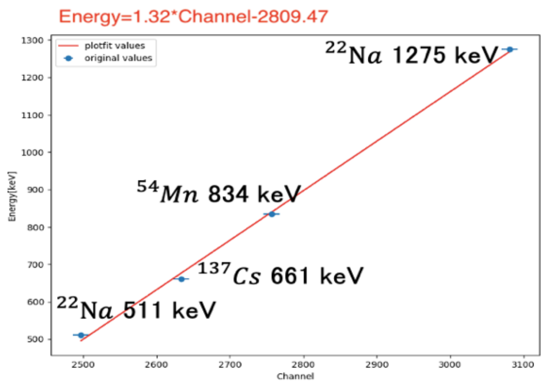

Figure 14: The linearity between channel and energy

GYRO SENSOR

There is no attitude control system in ARICA. However, the attitude information will be beneficial to understand the positions of antennae when the data are received or not. Therefore, we introduce BMX055 (BOSCH Sensortec Inc.), which is an absolute orientation sensor combining accelerometer, gyroscope and magnetometer in the class of 9-axis measurement units (Fig.15). The communication can be achieved by I^2C. This sensor is installed on the back-end board and the size is 14 x 10 mm.

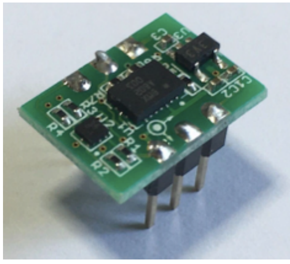

Figure 15: Gyro sensor (BMX055)

COMMAND & DATA-HANDLING (C&DH)

Field Programmable Gate Array (FPGA)

In ARICA, FPGA works as the controller of all systems. For example, in the case of data handling, FPGA generates the data communicating with GPS, EPS and the gamma-ray detector and sends them through SBD and Eyestar-S3. FPGA also handles the uplinked commands from SBD to change the configurations of the ARICA system. The FPGA is Artix-7 (Xilinx Inc.) and implemented it on the GROWTH board as shown in Fig.16.

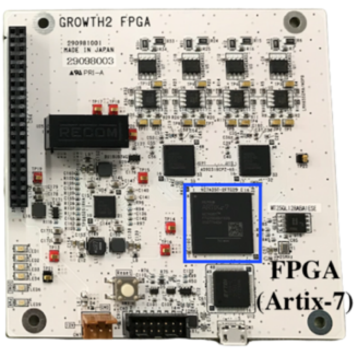

Figure 16: FPGA (Artix-7) in GROWTH board

ELECTRICAL POWER SYSTEM (EPS)

Clyde Space 3rd Generation (3G) EPS

The EPS of ARICA is a flight qualified product of AAC-Clyde Space Inc. The EPS connects to the solar panels via several independent Battery Charge Regulators (BCR). The solar panels are also the flight products of AAC-Clyde Space Inc. The outputs of BCRs are then connected together and supply charge to the battery through Power Conditioning Modules (PCM) and Power Distribution Modules (PDMs) (Fig.4). The telemetry node allows to monitor the operations of the EPS, control switchable buses and reset the power supplies if this is required. These TTC nodes are made using I^2C interface. The PDMs (switches) are available for two 12V, three 5V, three 3.3V supplies. These switchable powers are connected to Eyestar-S3, the HV module of gamma-ray detector and the gyro sensor (Fig.17). The GROWTH board (FPGA) and SBD are using non switchable power buses to always power the devices.

ARICA's battery is also the product of AAC-Clyde Space Inc. We chose the 20 Whr supply battery because of the cost and the capacity of ARICA. Each device's power consumption is given by Table 1.

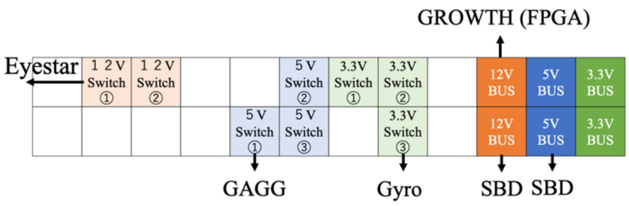

Figure 17: Power system diagram

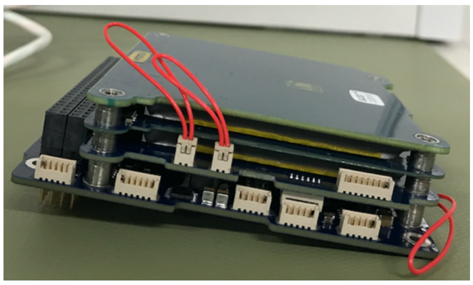

Figure 18: CS integrated EPS-20 Whr battery

DATA DESIGHN

As previously mentioned, our communication devices (SBD/Eyestar-S3) have the limits in the sizes of the message. Therefore, it is important to select the necessary data and design the data appropriately. The current data design includes the output voltages and currents of EPS's 3.3/5/12V buses, the GPS positional and time information, the counts in four energy bands of the gamma-ray detector, and so on. Based on current design, the size of the data are 72 bytes for SBD data and 32 bytes for Eyestar-S3.

OPERATIONS OF ARICA

ARICA has two operation modes, which are GRB mode and Housekeeping (HK) mode. When the spacecraft receives a command or the trigger signal from the gamma-ray detector, ARICA switches to the GRB mode. The spacecraft generates the burst data and send the data every second for a minute. If there is no trigger information, the spacecraft generates the HK data and sends the data every minute (HK mode). The operational flow is shown in Fig.19.

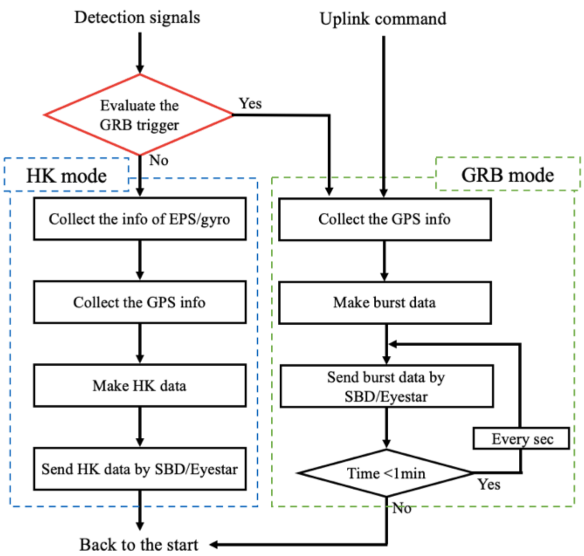

Figure 19: ARICA system operation

SUMMARY

We are constructing the 1U CubeSat ARICA to demonstrate the real-time alert system of transient astronomical source such as GRBs using the commercial satellite networks. The construction of the flight model of ARICA will start around this fall to be ready for a launch on Japanese fiscal year 2021 as a part of the JAXA Innovative Satellite Technology Demonstration-2.

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