DEVELOPMENT AND IN-ORBIT RESULTS OF THE APSCO STUDENT SMALL SATELLITE SSS-2A

Shufan Wu [(1)], Zhongcheng Mu [(1)], Qiang Shen [(1)], Qamarul Islam [(2)]

[(1)] *School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai 200240, China, shufan.wu@sjtu.edu.cn*

[(2)] *Institute of Space technology, P.O. Box 2750, Islamabad 44000, Pakistan qamarul_islam@hotmail.com*

ABSTRACT

The Student Small Satellite (SSS) project is an educational and training program for university students to have hands-on experience on the satellite design, development, and implementation practice. It consists of 3 Micro/Nano satellites forming an in-orbit small constellation for technology demonstration and some in-orbit experiments. SSS-1 is a microsatellite of 30kg mass, SSS-2A and SSS-2B are both 3U CubeSat. This paper presents the SSS-2A satellite design, development and in-orbit experiment results. Moreover, some lessons and suggestions are summarized for CubeSat development.

1. MISSION INTRODUCTION

Asia-Pacific Space Cooperation Organization (APSCO) has launched the Student Small Satellite (SSS) mission, which aims to train the students and faculties from Member States (MSs) of APSCO to study space technology and satellite engineering through practical design of satellites, and meanwhile contribute to the development of space education systems in APSCO MSs. The ultimate goal of this project is not only to enable universities to undertake student satellite design and development, but also to impart space technologies through a satellite project as well as hands-on training. Therefore, one of the most important and special aspects of the project is training and education.

The SSS project involves designing, constructing and launching three student satellites, one micro-satellite named SSS-1 and two CubeSats named SSS-2A and SSS-2B, respectively. The SSS-1 CubeSat is a 30kg micro-satellite with dimension of no more than 350mm × 350mm × 650 mm, led by Beihang University in China and with Iran and Pakistan teams supporting the development. Both the SSS-2A and SSS-2B are standard 3U CubeSats. SSS-2A is developed mainly by Shanghai Jiao Tong University in China with support from the Institute of Space Technology of Pakistan. SSS-2B is another 3U CubeSat, being developed by a team from Turkey, together with support from Thailand. The above three satellites construct a constellation named as APSCO SSS system as shown in Fig.1.

In this paper, the SSS-2A satellite design and in-orbit commissioning results are discussed. Some lessons from the project is summarized and shared, which is expected to offer the experience to a help on other CubeSat missions. This paper is organized as follows. Section 2 describes the design of SSS-

2A CubeSat. Some in-orbit commissioning and experiment results are presented in Section 3. Section 4 summarizes the learned lessons from the project. Section 5 concludes the paper.

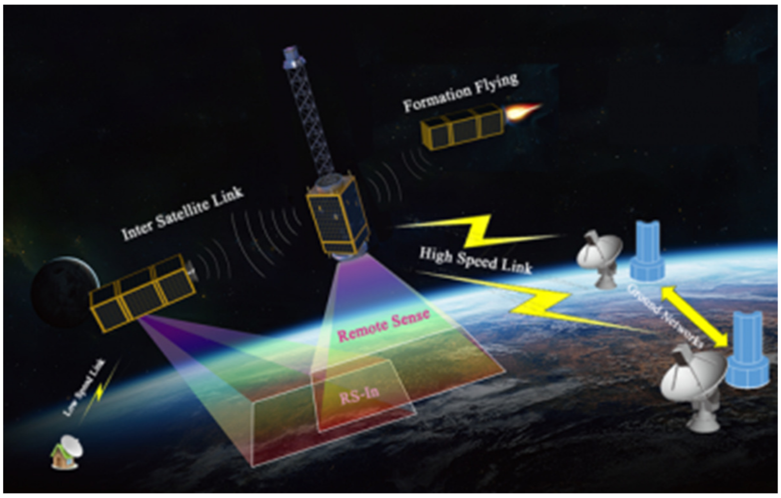


Fig.1 The SSS constellation to be constructed.

2. SATELLITE DESIGN

SSS-2A is a 3U CubeSat with body mounting and deployable solar panels, with a passive thermal control except for battery where a heater is applied to ensure certain temperature. Fig.2 shows the external layout of SSS-2A. The satellite chooses a solar synchronous orbit of 500km altitude with 10:30 AM as local time of descending node.

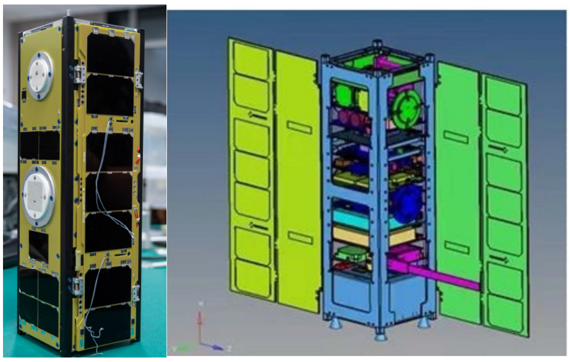


Fig. 2 SSS-2A external equipment layout.

Fig. 3 shows a general system configuration diagram of SSS-2A, indicating data flow, subsystem components and RF connections. It is designed and developed according to international CubeSat standard, which mainly includes payload, structure, thermal control, electrical power system (EPS), on-board computer (OBC), attitude and orbit control (AOCS), TT&C, data transmission and other subsystems. Based on the mission objectives and tasks assigned to SSS-2A, the satellite system specification is determined as given in Table.1. The layout of each single machine and its corresponding components on the satellite is shown in Fig.4.

2.1 Structure system

The SSS-2A satellite adopts a standard 3U CubeSat structure, with a frame panel design and single machine stacked installation. It adopts a penetrating structure composed of simple components, which greatly ensure the mechanical conditions, installation space and location for the payload and each subsystem to meet their functional, mechanical environmental and electromagnetic compatibility requirements. What's more, the satellite frequency characteristics should meet the requirements from its launch vehicle, the transverse fundamental frequency of the entire satellite shall be greater than 20Hz, and the longitudinal and torsional fundamental frequency shall be greater than 50Hz. The fundamental frequency of each direction should not be within 40±5Hz. The framework structure of SSS-2A satellite is shown in Fig.5.

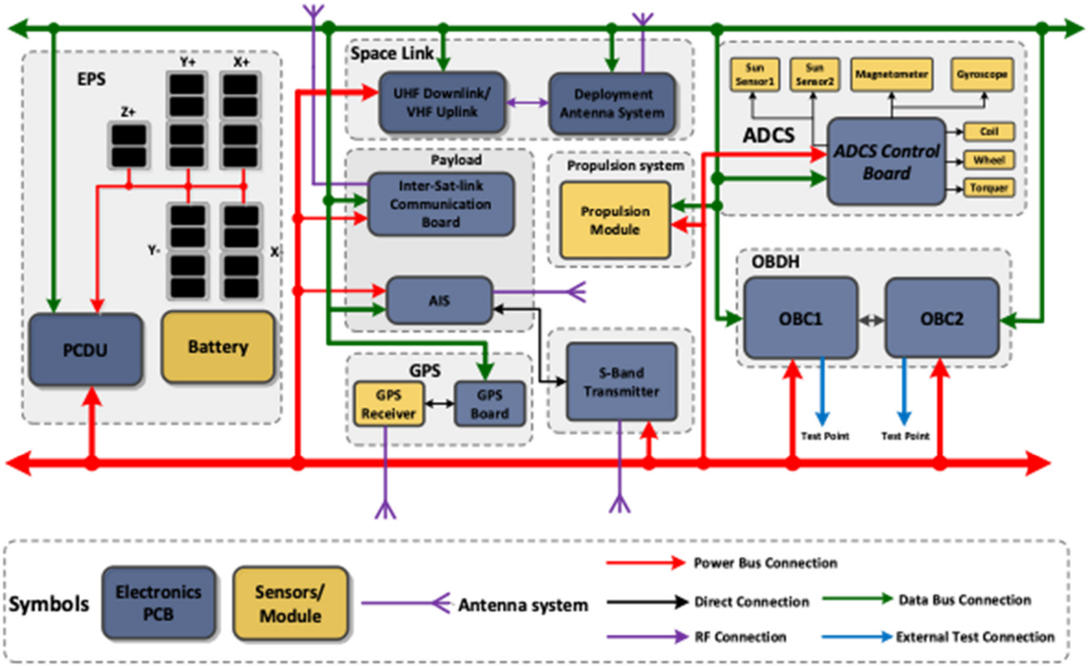


Fig.3 SSS-2A system block diagram.

Table.1 SSS-2A system specifications.

Subsystem	Item	Specification
Structure	Dimension	$340.5 \times 100 \times 100mm$
ADCS	Attitude determination accuracy	$\leq 2°(3\sigma)$
	Pointing Accuracy	$\leq 5°(3\sigma)$
	Pointing Stability	$\leq 0.1°/s$
Thermal	Internal temperature	$-10 \sim +35°C$
EPS	Bus voltage	10V ~ 12.6V
	Battery properties	2.6Ah, 1 year lifetime
TT&C	Frequency	UHF/VHF
	Modulation	BPSK
	Uplink	1200bps
	Downlink	9600bps
Data Transmitter	Date rate	Maximum 20Mbps
	Frequency	S band
	Modulation	QPSK
OBC	Process capacity	>20MIPS
	Process storage:	RAM>2M, Flash>256K

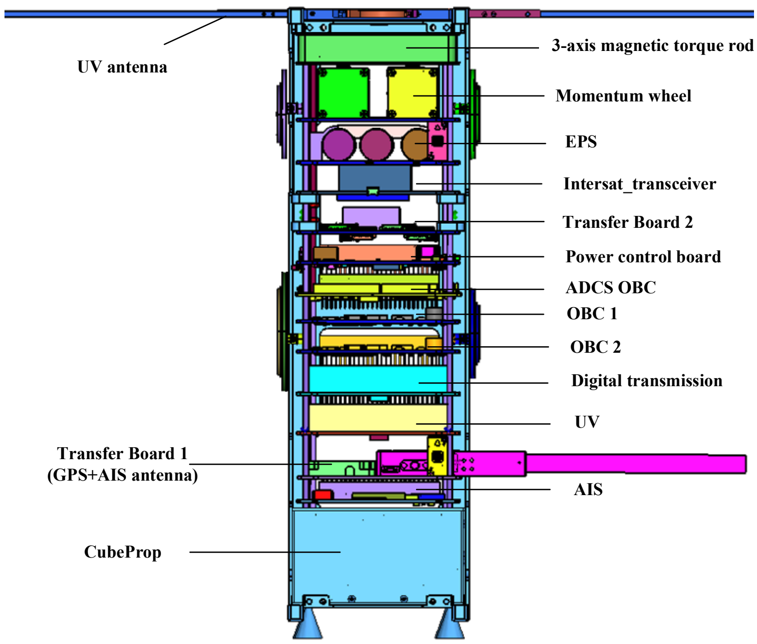


Fig.4 The layout of SSS-2A satellite

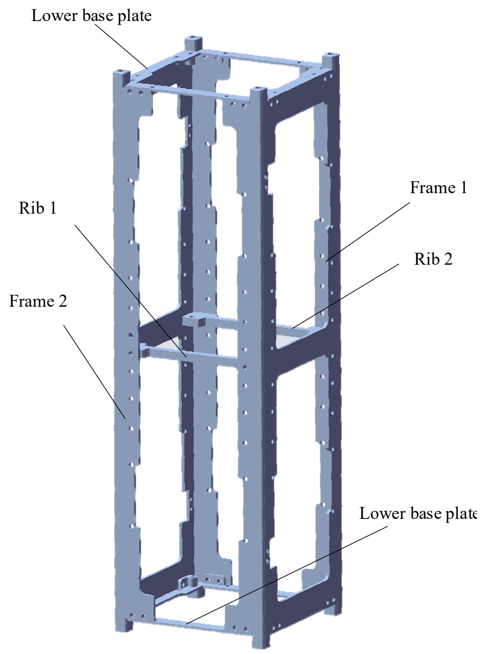


Fig.5 The SSS-2A structure

2.2 Thermal system

The satellite thermal subsystem is to ensure that all equipment on board meets their thermal control index requirements throughout the lifetime of the satellite starting from the launch segment. In order to improve the reliability of the thermal control subsystem and to reduce the demand for on-board mass, energy and other resources, SSS-2A adopts a combination of passive and active thermal control principles. It controls the temperature of the whole satellite to be in the range of -10 to 45℃. Thermal control design mainly includes heat dissipation surface design, heater power design and other aspects. The existing high emissivity solar cells and FR4 surface of the satellite are used for heat dissipation. Internal components and PCB exchange heat with the surrounding cabin board through radiation to meet its heat dissipation requirements. The heat dissipation surface design is shown in Fig.6. Constrained by the energy design and considering the temperature sensitivity and low temperature intolerance of the battery pack, the heater is set near the battery pack installation area to conduct closed-loop temperature control of the battery pack. The maximum power of the heater is 1W.

2.3 On-Board Computer (OBC) subsystem

The satellite OBC subsystem adopts a core processor based on ARM7 architecture and a CAN bus communication protocol. It takes the task of managing and processing the whole-satellite data, schedules satellite task, manages and controls operation of satellite equipment and modules efficiently and reliably, manages the time on the satellite, collects and monitors the satellite status, and coordinates with the payload subsystem to complete on-orbit mission. The OBC of SSS-2A consists of 2 cold backup board components, each board has the same design, and Fig.7 shows the OBC board.

The application software running on the satellite OBC, which is referred as Satellite Flight Software or simply Flight Software (FSW), can be regarded as a system-level entity. It plays a relevant role in implementing space mission to meet complex requirements and is the main interface during the space mission operational phase. The FSW provides all the necessary functions for nominal operations of the satellite. Moreover, it enables the ground users to control and to supervise its various sub-systems for the whole mission. Additionally, the FSW manages the mission phases, the satellite modes, the ground interface, the AOCS, the thermal control, the satellite health managements (also referred to as Failure Detection, Isolation, and Recovery (FDIR)), and the on-board mission operation execution. The FSW is in charge of managing the decision-making processes with limited autonomy degree.

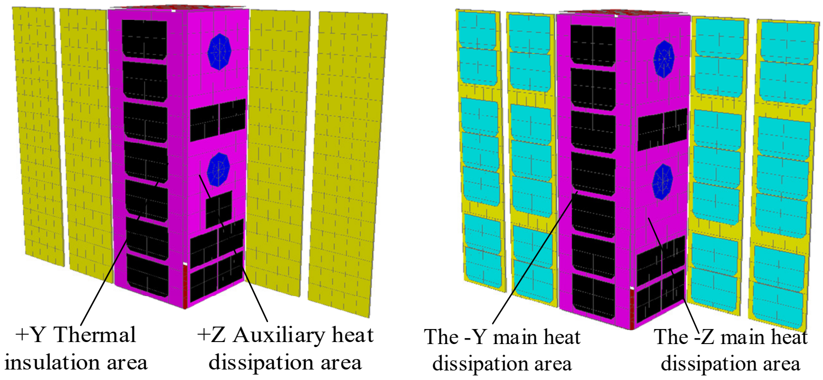


Fig. 6 Schematic diagram of satellite heat dissipation surface design

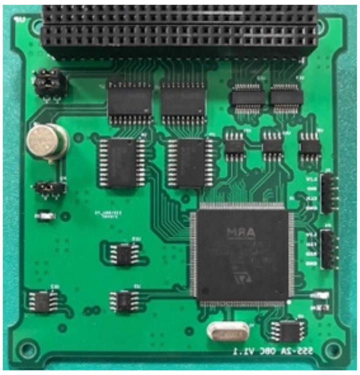


Fig.7 The on board computer.

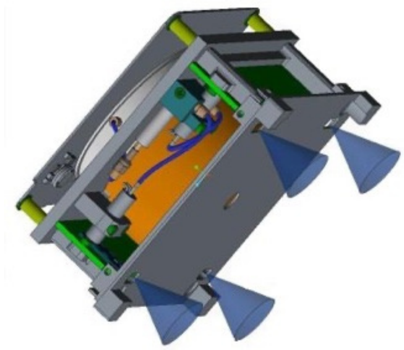


Fig.10 The MEMS Micro-propulsion system.

2.4 Electrical Power System (EPS)

For the EPS, a space-proven COTS product for CubeSat is chosen. Its photovoltaic solar panel can supply over 30W power. A maximum power point tracking (MPPT) circuit is adopted for optimal power generation. It has 3 input channels which can set the power-point with 3 different options independently. The measures for battery under-voltage and over-voltage protection are taken. It provides a regulated power bus of two 5V and one 12V. The EPS package is shown in Fig.8.

Fig.8 The electrical power system.

In the simulation, after SSS-2A being released in orbit, each orbit period has a light time of 59.84 minutes and a shadow time of 34.78 minutes. Average power output of the solar array each orbit is 14.98W. When the CubeSat is in shadow zone, the Lithium-battery alone can supply over 20W power, when in solar zone, the battery and solar panels can together provide over 30W power together.

2.5 Communication System

For TM/TC, a UHF downlink and VHF uplink full duplex transceiver is chosen and the data rate is chosen as 9.6kbps to leave more communication budget margin though the selected transmitter has a much higher capacity. For data transmission, an S-band transmitter is used, working at a frequency of 2405MHz. Except as a downlink for payload data, the S-band transmitter is also used as a backup of TM/TC. Fig.9 shows the UHF/VHF transceiver and the USB transmitter.

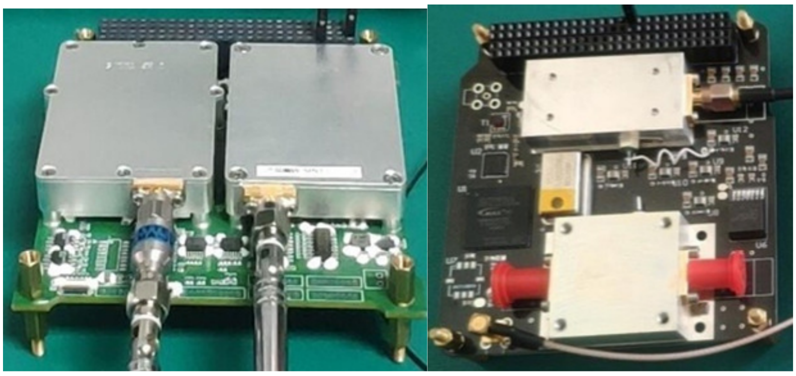


Fig.9 UHF/VHF transceiver and USB transmitter.

2.6 Attitude and Orbit Control Subsystem （AOCS）

The AOCS is designed for the required spacecraft control during all mission phases. Its major tasks include:(1) stabilization of the spacecraft after separation from the launcher, (2) autonomous attitude acquisition and determination, (3) stabilization and control of the attitude in 3 axes, (4) orbit maneuver during formation flying. Table.2 shows the main configuration of the AOCS in SSS-2A, and sensors and actuators being used.

Table.2 Configuration of the AOCS system.

Unit	Item
Fine sun sensor (×2)	FOV: $120°C$ Accuracy: $\pm 0.5°$ Sampling period: 10ms
Ggyroscope (×1)	Range: $-225°/s$ $225°/s$ Accuracy: $0.007°/s$
Magnetometer (×2)	Range: -400000~400000nT Resolution: 700nT Sampling period: 10ms Output frequency: 10Hz
Magnetorquer (×1)	Magnetic moment: > $300mAm^2$
Reaction Wheel (×4)	Nominal rotating speed: ±8000rpm Nominal torque: 0.023mNm Momentum storage: 1.77mNms

The ADCS has 3 working modes in orbit, detumbling mode, sun pointing mode and nadir pointing mode. After separation, the SSS-2A will use magnetometer, gyro and magnetorquer to damp the initial angular rate of the CubeSat, with the Bdot control scheme. The magnetic moment of the magnetorquer interacts with the Earth magnetic field to generate a control torque to damp the rate.

At the end of the rate damping, the sun pointing will be entered for energy charging. The magnetorquer is used to implement the sun pointing mode, and the attitude sensors involved are sun sensors and magnetometers.

In the nadir pointing mode, the dual-vector attitude determination method is applied with the magnetometer and the sun sensor outputs. When in the shadow area or the sun sensor output is invalid, the double vector EKF attitude setting scheme is adopted; the 3-axis reaction wheel is used for the main attitude control actuators.

The magnetorquer can be used to unload the speed of the momentum wheel. When there is a reaction wheel failure and the Y-direction reaction wheel is normal, the three-axis wheel control scheme is switched to a biased momentum control mode. If the Y-direction reaction wheel fails, a three-axis magnetic control scheme is adopted.

Fig.10 shows the MEMS Micro-propulsion system, it can carry 50g propellant and provide 4mN thrust (1mN each nozzle) for orbit maneuver during formation flying. The volume of the propulsion module is 10×10×5cm, a standard CubeSat component.

The orbital control strategy design of the orbital mission needs to comprehensively consider the constraints of propulsion, measurement and control, attitude control, etc., and arrange the orbital control reasonably, so that the control quantity can meet the accuracy requirements of the measuring rail within the scope of propulsion capability, and it has the feasibility of measurement control, in line with engineering practice. Parameters of propulsion system are listed in the following:

(1) Total thrust: 4 mN (including 4 nozzles, 1 mN for each nozzle);
(2) Minimum thrust: 5 μN;
(3) Minimum thrust adjustment step size: 5 μN;
(4) Minimum pulse width time: 1 ms;
(5) Longest pulse width: 30 min.

2.6 Payload system

SSS-2A has two payloads, an Inter-Satellite Link (ISL) module and an Automatic Identification System（AIS）module. The ISL payload is developed in house at Shanghai Jiao Tong University, as shown in Fig.11. It is developed based on two novel technologies: Software defined Radio (SDR) and Mobile wireless Ad hoc networks. The device has two segments: the space segment and the ground segment. The space segment includes the ad hoc network capability for ISL, a GPS receiver and a radio-based attitude determination algorithm.

The AIS is an automatic tracking system that uses transponders on ship and is used by vessel traffic services (VTS). The ship-based and shore-based AIS system is limited by the distance, the ability in global ocean monitoring does not perform well. With the development of CubeSat, Sat-based AIS system can provide large-scale service for e-Navigation, and Ocean Information Services, Onboard SSS-2A, the AIS receiver is developed in house and the technology is going to be validated. It consists of receiver and antenna, where the receiver is attached on a PCB board and it has a standard PC104 CubeSat interface, as shown in Fig.12.

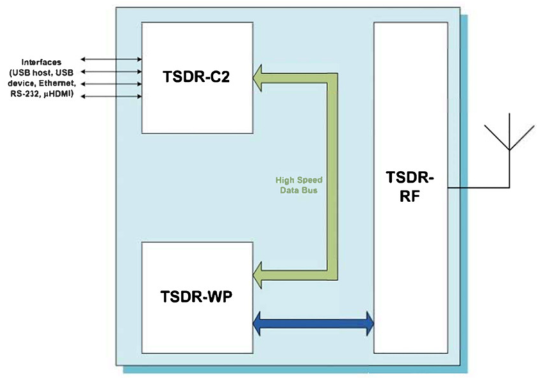


Fig.11 The inter-sat communication payload.

Fig.12 The AIS payload.

3. IN-ORBIT COMMISSION AND EXPERIMENT RESULTS

SSS-2A CubeSat was launched at the Taiyuan Satellite Launch Center at 18:51 on October 14, 2021, on-board an LoangMarch-2 launcher, and entered the desired LEO orbit of Sun-synchronous orbit (SSO) at 19:05:25 on October 14, 2021, with an altitude of 500 km, and LTDN at 10:30 AM.

3.1 In-orbit commissioning

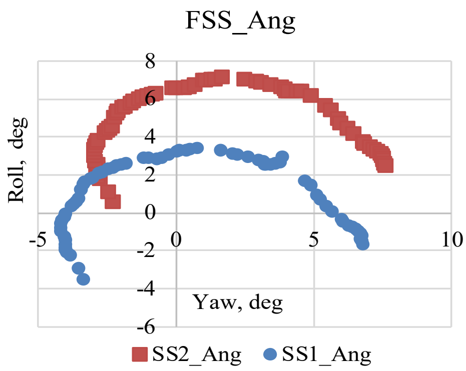
For mission operation, two UHF ground station are set up in Shanghai and Xinjiang, respectively. After being released from the launcher, the electrical power was switched on automatically. A series of self-inspection and preparation commands were executed. The ground station in Xinjiang Province accessed the SSS-2A CubeSat on its first orbit pass after the launch at 20:32:32 on October 14, 2021. The first package of data received in Xinjiang indicates that the CubeSat executes the program according to the preset flow, UV antenna, AIS antenna and solar panels are unfolded smoothly. Moreover, the satellites had already completed the rate damping mode and the angular rate of SSS-2A had been reduced to be within 1.2 deg/sec, entering into the sun pointing mode automatically. It is worth mentioning that owing to a long-term power-off before launching, the first package of TM data shows that the bus voltage of satellite is 11.8V which is still normal.

The ground station in Shanghai then received TM data at 07:22 a.m. on October 15, 2021. It shows the bus voltage rose up to 12.4V. Then a series of actions were executed in the following days from Shanghai station. All the mission payloads were successively switched on, numerous valid data were received respectively. After a successful commission phase, the sub-systems of the platform and the payload testing work are carried out steadily.

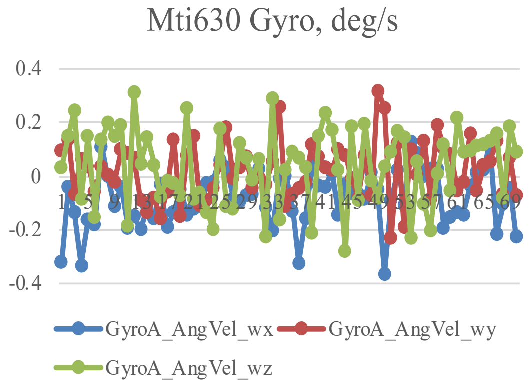
3.2 In-Orbit Status

By November 16, the SSS-2A has been in orbit for more than 30 days, all the subsystems work well, and the satellite telemetry monitoring data fall within the design specifications. The OBC sub-system shows a reliable and effective support for various in-orbit tasks. Functions of time management, TM&TC, backup device switch and payload control on OBC system have all been validated well. The EPS system could provide stable power supply and temperature control.

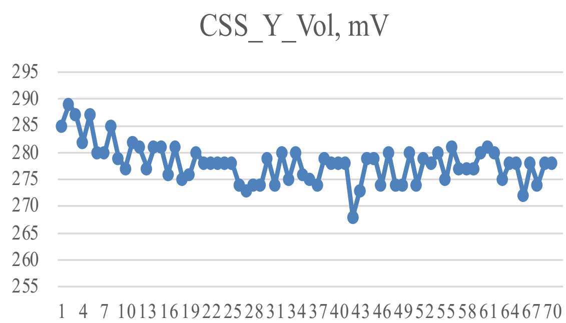
The AOCS provides a stable attitude control for tasks such as inter-satellite communication and payload on-orbit test. The on-orbit data shows that in the zero-momentum three-axis wheel control mode, the roll and yaw angle measured by fine sun sensors are less than 10°, the angular velocity measured by gyros is less than 0.5°/s, and the three-axis momentum wheel maintains a good response to the command signal. Some in-orbit results are shown in Fig.13. The satellite maintains a stable attitude towards the sun to ensure that the satellite solar sail is in a good charge and discharge state.



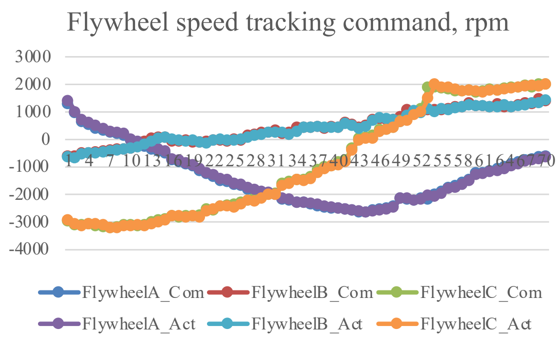
(a) Precise sun sensor roll-yaw remote measurement



(b) Gyro remote measurement-three-axis rotation speed



(c) Coarse sun sensor measurement-+Y direction voltage



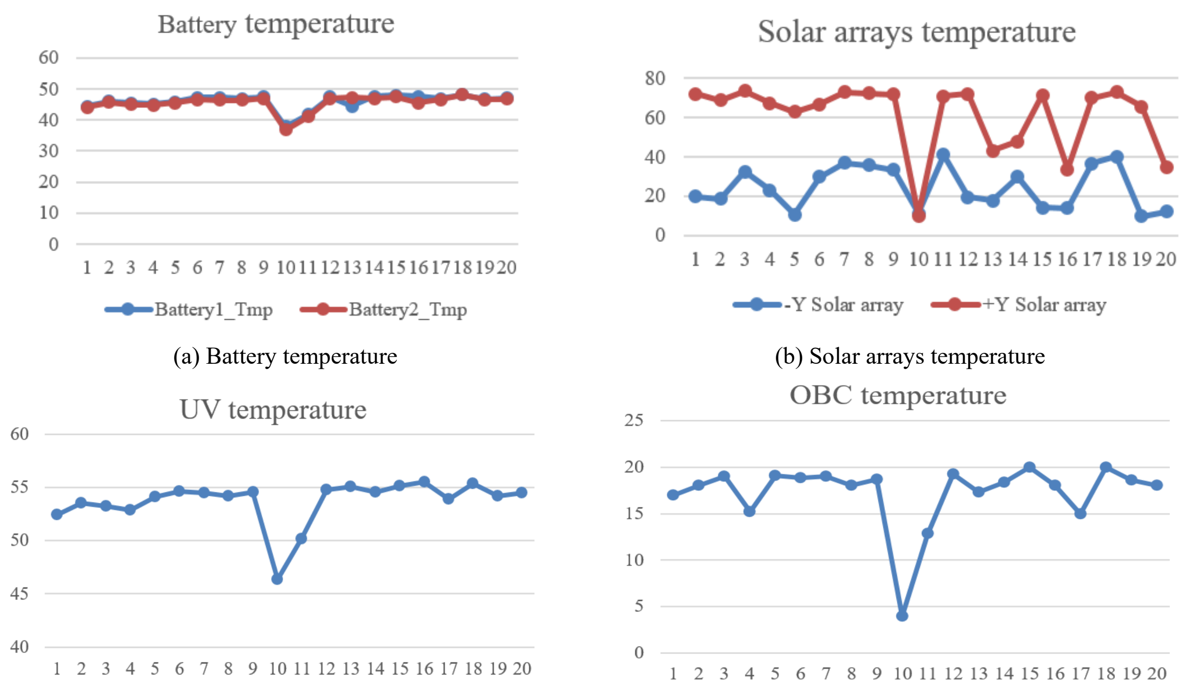
(d) Flywheel measurement-commanded and measured speed

Fig.13 TM data of AOCS

Meanwhile, the structure and thermal subsystem is demonstrated to be also in a good and stable state in orbit through the statistical analysis of satellite telemetry data in the past month. The temperature of the battery is always about 40℃. The temperature of the solar array in the positive Y direction does not exceed 70℃, and the solar panel temperature in the negative Y direction is stable at about 35℃. The temperature of the UHF/VHF machine for measurement and control is maintained at about 55℃, and the temperature of the OBC fluctuates around 20℃. The on-orbit temperatures of all subsystems are within the designed range, which fully ensures the safe in-orbit operation of the whole satellite. Some detailed results are shown in Fig.14.

3.3 Radio Communication Forwarding

The communication transponder developed in-house by the team is operating well. The UHF/VHF measurement and control communication machine is in good working condition. The uplink remote control command reception and downlink remote measurement data transmission functions are stable, and the satellite-to-ground data forwarding experiment is carried out steadily. The satellite downlink frequency is 435.775MHz. The SSS-2A satellite has the function of amateur radio communication, and the parameters of the transponder are exhibited in Table.3. At present, some amateurs have received signals from the SSS-2A satellite. The communication transponder is shown in Fig.15 (a) and obtained downlink signal spectrum through ground station software is given by Fig.15 (b).



(a) Battery temperature

(b) Solar arrays temperature

(c) UV temperature

(d) OBC temperature

Fig.14 TM data of thermal subsystem

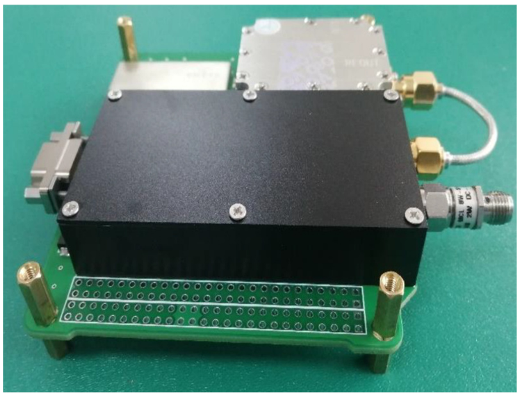
Table.3 The parameters of transponder

Parameters	Value
Receiving frequency	145.890MHz
Transmitting frequency	435.645MHz
Transmitting EIRP	27dBm
Forwarding bandwidth	30KHz
Forwarding mode	Linear forward
ITU registration name	CAS-8

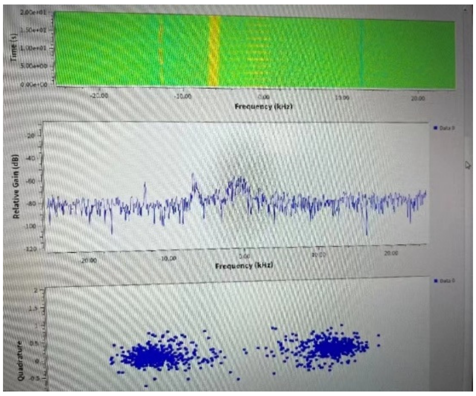
Aiming at verifying the forwarding function of SSS-2A, we set up two UV ground stations in Minhang District and Xuhui District in Shanghai, respectively. We carried on the forwarding test at 18:30 on December 31, 2021, when the two UV ground stations are simultaneously visible to the satellite. The station in Xuhui District transmits the uplink signal, simultaneously, the station in Minhang District receives the downlink signal. We have uploaded the testing video on Google drive, just scan the QR code in Fig.16 to access.

3.4 AIS receiver

One the second day after the launch, when the SSS-2A passed over Shanghai, we upload a tele-command to switch on the AIS receiver as the first trial. The signals received by AIS receiver were decoded onboard the satellites to get the necessary information, including ship name, MMSI, length, position, heading, speed, distance from the main channel and the timestamp as well. Then the receiver will storage the decoded data in self-contained SD card. The next time the satellite passed over Shanghai, it transmitted the collected data to ground station. The accumulative data over two orbits (October 16, 2021, 20:30 PM- October 17, 2021,00:30 AM) is illustrated in Fig.17, which shows that most ships are concentrated around the coastlines of Asia and South America, and there are few ships in the Antarctic circle, but a few in the Arctic Circle. SSS-2A is expected to collect more information about world-wide ships.



(a) Satellite communication transponder



(b) Satellite downlink signal spectrum diagram

Fig.15 The transponder and its downlink signal spectrum

Fig.16 The QRcode linking to the forwarding test video

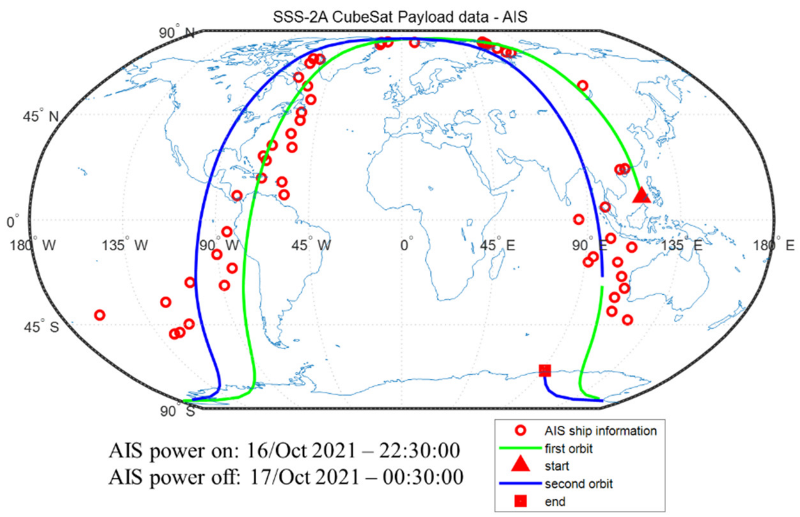


Fig.17 SSS-2A capture ship signal over two orbits

3.5 Inter-satellite communication experiments

In order to carry on inter-satellite communication experiment, an attitude alignment with Beihang's satellite SSS-1 is performed on November 17, SSS-2A has successfully received the data sent by SSS-1. The valid data of inter-satellite communication from SSS-1 are given by the on-board computer through serial port, which contains the information of satellite time and attitude. The detailed information of the transmitted data is illustrated in Table.4.

Table.4 The detailed information of the transmitted data

Content	Description	Bits
Frame header	0xEB90	16 bits
Satellite time	Second ++	8 bits
	Second +	8 bits
	Second -	8 bits
	Second --	8 bits
	Millisecond +	8 bits
	Millisecond -	8 bits
Attitude angle	Angle of roll	16 bits
	Angle of pitch	16 bits
	Angle of yaw	16 bits
Attitude angle velocity	Angle velocity of roll	16 bits
	Angle velocity of pitch	16 bits
	Angle velocity of yaw	16 bits
Reserved	0xAA	12 bits

The original data of inter-satellite communication received by SSS-2A at 17:44:14 (Beijig time) on November 17 are as follows: EB 90 07 4B 54 EE 94 38 FF FD 00 01 FF FE 00 01 00 06 FF FF AA AA AA AA AA AA AA AA AA AA AA AA. The original data and decoded data are listed in Table.5. It needs to be noted that satellite time is corresponding to UTC time, and Beijing time is 8 hours early. It proves that the inter-satellite link is established successfully and the inter-satellite communication verification experiment is completed.

Table.5 The original data and decoded data

Content		Data	Decoded information
Frame header		EB 90	/
Satellite time	Second ++	07	Second value of satellite time: 122377454 s UTC: 2021-11-17 9:44:14
	Second +	4B	
	Second -	54	
	Second --	EE	
	Millisecond +	94	Millisecond value: 948.6 ms
	Millisecond -	38	
Attitude angle	Angle of roll	FF FD	-0.017
	Angle of pitch	00 01	0.006
	Angle of yaw	FF FE	-0.001
Attitude angle velocity	Angle velocity of roll	00 01	0.001
	Angle velocity of	00 06	0.004

	pitch Angle velocity of yaw	FF FF	-0.001
Reserved		AA*12	/

4. LESSONS LEARNED

Through the design, development, testing, and in-orbit experiments of the SSS-2A satellite, some lessons can be drawn out as summarized below.

(1) Developing process and specifications:

a) The developing process follows the plan-prototype stage and the product strategy of engineering-projectile parts is adopted, which greatly shorten the development cycle and save development costs. Additionally, it conforms to the characteristics of CubeSat - small, light, fast, and economical.

b) The standard spacecraft development specifications and testing methods need to be tailored for CubeSat development, to form a simplified approach of design methods and testing procedures suitable for CubeSats.

c) The experience in screening and using low-cost components through the use of commercial or industrial-grade components for on-orbit applications of CubeSat is very important.

(2) Satellite Design:

a) The function of core parameters updating in-orbit is very important for any needed changes in spacecraft parameter after launching. Additionally, the core software on-orbit needs to be modularized sin order to be capable for in-orbit updating.

b) Based on the thermal model of the PCB-based satellite body, and combined with the analysis and model checking of the leakage heat source in the thermal test, a practical approach for thermal design and analysis is found suitable for CubeSats， which has has been verified through the on-orbit telemetry data.

c) In CubeSat, many low-level and low-reliability components are used, the distributed and heterogeneous redundant backup design shall be considered in the system design. Additionally, the fault tolerance and error correction capability can be strengthened via software upgrades.

(3) Follow-up suggestions:

a) SSS-2A uses the UHF amateur radio frequency band for telemetry. Through the analysis of in-orbit telemetry data, it is found that the noise floor in southeast, southwest, and north China is 10-20dB higher than that in other parts of the world such as Europe and the United States. Therefore, it is better to consider the ground interference factors in the satellite-ground measurement and control link when using amateur radio frequency band, and more margins are needed to ensure the reliability of the satellite-ground communication;

b) The successful in-orbit application of SSS-2A shows that CubeSats can not only be used for new technology exploration and testing but also provide effective on-orbit application value. Due to the CubeSats' characteristics of small size, light mass, and simple interface, it is recommended to make full use of the surplus of rockets to carry more CubeSats for scientific tests, promoting the vigorous development of new satellite technologies and applications.

5. SUMMARY

This paper presents the SSS-2A mission, which was designed to explore marine traffic information collection and monitoring, and CubeSat-size ISL module based on the low-cost off-the-shelf CubeSat technologies.

Mission analysis, satellite design, in-orbit commission, operation, and test results are presented to illustrate the various aspects of the mission, with practical results being elaborated. Some practical lessons or experiences are drawn out, which could be very useful for future CubeSat mission and further extension of CubeSat missions.