Development of an Integrated Separation System for Sea Retrieval of a Small Zero-Pressure Balloon*

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1. Introduction

Although scientific ballooning has an advantage of being able to retrieve payloads after a flight mission, payloads that separate above the ground could cause safety issues such as road blockage or house damage. To remedy this problem, the renowned Japan Aerospace Exploration Agency and Institute of Space and Astronautical Science (JAXA/ISAS) have developed a distinctive sea recovery strategy. This method retrieves the jettisoned payload at sea instead of the ground in order to ensure the safety and sustainability of the balloon campaign in Japan.1) New issues will inherently arise when sea recovery is conducted. For example, if the sea recovery operation fails, the envelope made of a polyethylene film may not only cause marine pollution but also raise the potential threat of becoming entangled in the propellers of ships.2) As such, the envelopes should be retrieved after the mission. JAXA/ISAS developed two types of Iridium flight buoys that transmit GPS position data in a specific interval to facilitate sea recovery operations. The weights and lengths of the two buoys are 1.5 kg and 40 cm and 5.8 kg and 75 cm, respectively.3) Even though the buoys contribute to successful sea recovery operations, they could impose a burden on small zero-pressure balloon (ZPB) in terms of weight and size constraints. The lighter and smaller buoy may be considered an alternative in view of this issue. However, the mini buoy can lead to tracking problem caused by immersion due to entanglement with the envelope.

To address the problems mentioned above, an integrated separation system (ISS) was developed for retrieval of the small ZPB envelope. This system is lightweight, compact, and is able to float, even when entangled with the envelope. In addition to tracking ability, it has a separation function incorporated to serve as a standalone platform. For reliable operation of the ISS developed when used at sea, several salient features were considered in the preliminary design stage. These features include waterproofness, flotation, short-circuit prevention, impact resistance, and non-line-of-sight (NLOS) communication. The ISS is also designed to fulfill as a standalone flight platform that takes into account research demands of lightweight payloads, such as a space environment simulation test of a CubeSat, and space atmospheric measurement using ozone sensors and aerosol impactors. The performance and reliability of the ISS were proven through four flight tests using rubber balloons and ZPBs.

2. Development of the ISS

2.1. Mission profile and operational requirements

We aim to install the ISS on small stratospheric balloon platforms with a 10–30 kg payload capacity depending on the given mission. This balloon is designed to carry out university-based scientific observation and technological experimentations in the stratosphere after taking into account regulatory restrictions on airspace usage and geographical constraints of South Korea. Therefore, the ISS is exposed to low-pressure/temperature environment during the flight window: launch, ascent, mission, flight termination, and retrieval at sea. It is also highly probable that the ISS may be exposed to troublesome situations such as immersion by sea waves or a NLOS situation due to low altitude. To overcome these inadmissible situations, the following requirements were taken into account.

1) The ISS should operate more than 4 hr in harsh environments, such as temperatures below −40°C and an atmospheric pressure of about 1/100 that of the ground.
2) The jettisoned ISS should sustain flotation and waterproofness until retrieval has been completed.
3) The telemetry and telecommand system should be able to maintain reliable communication even in an NLOS situation for monitoring and controlling the ISS.
4) It must be lightweight and compact not only for use as a standalone platform, but also for suspending it with a small ZPB. Herein, the weight of the ISS chosen was less than 2 kg.

2.2. Waterproof and buoyancy system

To prevent immersion of the ISS after splashdown, the enclosure should be waterproof. In this regard, a commercially available polycarbonate enclosure was selected due to its high impact resistance, easy machinability and waterproof characteristics. The waterproof enclosure consists of an outer cylinder, upper cover and bottom cover, as shown in Fig. 1. A handhold and hook point are on the upper cover for the convenience of retrieving at sea. An O-ring was implemented between the upper cover and outer cylinder to seal the case. To prevent breakage caused by extreme pressure change in the

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stratosphere, a waterproof vent cap (Milvent®) was mounted. The fire initiator lead wires for activating the pyro-cutter and the ambient thermometer were designed to pass through the cable gland while maintaining waterproof performance. To prevent saline water-induced short circuiting, the power sources of the pyro-cutter and electronics were divided into two power sources rated at 18.5 V and 5 V, respectively. The maximum available time for the ISS is designed to last for more than 4 hr, assuming a 50% capacity reduction of the lithium-ion battery (LG 18650) due to low temperatures. It can operate for more than 9 hr at room temperature. The bottom cover is made of aluminum alloy because of its high strength. Three aluminum fixing bars were bolted between the upper cover and lower cover to prevent detachment incurred by impacts of the splashdown at sea.

Although the ISS can float itself, a slide-type buoy made of XPS was mounted below the upper cover. The reason for this is twofold: 1) maintaining a stable attitude against rough waves; and 2) providing additional buoyancy for averting immersion caused by the drag force exerted on the envelope. This slide-type buoy enable the GPS and Iridium antennas to transmit data flawlessly while pointing to the sky. The volume of designed buoyant material generates a buoyancy of 40 N in seawater, which is approximately twice the required value. After tying with a 20-kg weight to the ISS, it was immersed in a water-filled container for 6 hr to verify its waterproof capability. For the impact test, the ISS was subjected to two drop tests in a towing tank prior to the flight test. It was tested for freefall from a height of 5 m, assuming a maximum terminal velocity of 10 m/s. No breakage, immersion or short-circuiting were observed.

2.3. Separation mechanism

The separation mechanism consists of pyro-cutters and power-supply controllers (relay). The cutters must function well in harsh environments such as low-temperature/pressure. A pyro-cutter of the Pacific Scientific Company was utilized for separation. This cutter can operate in a temperature range between −54°C and 74°C, which satisfies the operating environment. Additionally, several flight tests using the ISS prototype showed that the electronics enclosed in the transparent polycarbonate case were kept in the normal operating temperature range due to solar irradiation in the stratosphere and heat dissipation from the electronics. Based on these data, the ISS electronics were predicted to remain within the allowable temperature range (0–55°C) during daytime flight. A COTS power relay module with a maximum switching current of 15 A was employed to control the power supply. The recommended all-fire current was 4.5 A. A supply voltage of more than 18 V was required to activate this all-fire function. To activate the fire function, the voltage source was designed as a power pack consisting of five 3.7 V lithium-ion batteries connected in series. A microcontroller that receives a separation command from the Zigbee or Iridium satellite communication operates the assigned relay. Aside from the remote control to activate the separator for flight termination, a programmable timer function was incorporated into this system for aviation safety. This timer was used as a failsafe device in case of an unexpected command failure or the loss of all radio links. The timer uses a clock function built into the microcontroller. The time can be set to different values depending on the flight mission, and is usually pre-programmed before launching the balloon. When the set time has elapsed, the separating mechanisms are activated. An additional feature of the timer is that the set time can be adjusted in real-time using a wireless system when a mission requires an extended flight time window after launch. Intervals of 30, 60, 90 and 120 min are possible without any trial limitations.

2.4. Telemetry and telecommand system

After flight termination is executed, the ISS is supposed to fall into a NLOS situation as it loses altitude. Therefore, it should have wireless communication independent of the LOS. It should also have a redundant wireless system for reliable separation command. The wireless system is classified into two categories as shown in Fig. 2. The primary system is the Zigbee, which is a short-range wireless system. A telecommand system installed on the basic onboard equipment (BOE) gondola receives a command signal transmitted from the ground station via a UHF frequency band. It then transmits the command to the ISS using the Zigbee. This primary system can activate separation immediately upon receiving the command, but the command cannot be executed when it is at NLOS situation. To address this drawback, the Iridium satellite communication system was selected as a secondary option. Although this communication system is not suitable for immediate transmission and reception of data due to server processing delay or weakened satellite signals, it provides global communication coverage. In addition, this system is an e-mail-based network that does not require construction of a spacious ground station for data acquisition and command. In this regard, it relieves the burdens of conducting scientific ballooning at the level of educational institutes.

2.5. Considerations as a standalone platform

According to International Civil Aviation Organization Aviation Annex 2, a balloon carrying a payload less than
4 kg is classified as a small balloon. A small balloon has less operating limitations compared to heavy balloons from the aspects of flight permission and failsafe equipment. In this regard, the ISS was designed to meet the weight constraints of 2 kg. This constraint was determined to accommodate the scientific and engineering payload weighing less than 2 kg, such as the CubeSats, an aerosol impactor, and ozone sensor.

The Zigbee communication system of the ISS enables construction of a short-range network for data acquisition and command. It features excellent scalability, with the capability of easily expanding or reducing the functions of the communication system based upon mission demands. For example, the Zigbee provides redundancy communication in conjunction with the BOE for small ZPB campaigns, which carry more weight than a 4-kg payload. However, for rubber balloon campaigns with payloads of less than 4 kg, the Iridium module is the sole telecommand device for both in-flight and sea recovery operations. This fact can broaden the usability of the ISS as a standalone platform. Owing to the achievement of weight reduction, rapid flight cycles with mission flexibility become possible for small balloon campaigns. Universal joints using eyebolts and nuts were bolted onto the protruding bases of the ISS lower part to improve compatibility with other experimental equipment.

3. Flight Tests Including Sea Retrieval Strategy

3.1. The configuration of platforms

Four flight tests focusing on sea retrieval were conducted to verify the performance reliability of the ISS. A rubber balloon with a weight of 1.5 kg and a small ZPB platform that can carry a 10-kg payload up to 20 km were used. The ISS developed was placed below the envelope, as depicted in Fig. 3. The weights of the rubber balloon and ZPB system were 3.98 kg and 20.16 kg, respectively.

3.2. Test results and discussion

A summary of the ISS flight test results is presented in Table 1. The results of the flight test on 27 May 2018 are presented as a case study in this paper.

Figure 4 shows the flight path and timeline of the ZPB platform. The envelope and BOE were recovered at points 156 km and 210 km, respectively, from the Samcheok launch site. The balloon campaign took 310 min from launch to the completion of sea recovery operations.

The GPS position and atmosphere measurement data of the ISS were received via the Iridium satellite during the whole flight window, even during the NLOS situation after flight termination. The altitude variation and vertical speed of the ISS based on GPS data are depicted in Fig. 5(a). After the launch, the ISS ascended for 70 min at an average speed of 3.7 m/s. The maximum altitude of the ISS was 15.6 km. This value was recorded 70 min after launch. The flight was terminated earlier than planned owing to safety concerns regarding the flight path deviation of the balloon from approved airspace. Base on the atmosphere data measured, the ISS was exposed to sub-zero temperature at an altitude of 6.5 km 30 min after launch, and then recorded a lowest temperature of −40.9°C as shown in Fig. 5(b). The internal pressure showed a linear decrease as a result of the ventilation cap installed. Therefore, no breakage of the polycarbonate cylinder due to internal and external pressure differences was observed. It also recorded a descent speed of 3.8 m/s just before splashdown. The initial assumption of the impact test was well comparable with this result.

Control commands employing the timer, UHF-Zigbee, and satellite communication were verified through previous ground and flight tests for land recovery. In these flight tests focusing on sea recovery, the UHF-Zigbee and Iridium satellite communication methods successfully severed the suspension line between the envelope and parachute. However, unlike UHF-Zigbee communication, which is performed instantaneously after receiving a separation command, satellite communication delay was observed. This phenomenon is shown in Fig. 5(a). The separator reached 15.6 km at 70 min, while the gondola went up to 16.4 km at 73 min. In this regard, it is conceivable that the latest status information was not transmitted in a timely manner due to the communication delay. The required time for receiving the ISS data via e-mail after measuring the GPS time is about 10 s under ideal conditions with maximum signal quality. However, it was found that the average required time varied from 38 to 127 s on average. It seems that sever processing delay and weaken signal strength brought these particular results. For this reason, it should be noted that an execution delay of control
commands may occur according to the signal strength of the Iridium satellite modem. After splashdown, the ISS transmitted the position data impeccably while keeping a stable posture at sea owing to the buoyancy of the XPS. The ISS showed the desired performance without leakage, immersion or short-circuiting of the electronics during the entire flight window. A photo of the ISS retrieved is shown in Fig. 6.

4. Conclusion

In this paper, an integrated separation system (ISS) for the retrieval of small ZPB envelopes was presented. The conclusion can be summarized in two parts.

First, for reliable operation of the ISS in harsh environments, salient requirements were taken into account. These requirements include waterproofing, flotation, short-circuit prevention, impact resistance, and over-the-horizon communication. In addition to this, the empty weight reduction of the ISS, which increases the usability, was realized to serve it as a standalone platform.

Lastly, as a standalone platform, the operational reliability and usability of the ISS developed were examined through four flight tests using rubber balloons and ZPBs. No breakage, immersion, and short-circuit were observed. Furthermore, the ISS was able to maintain telecommunications during the entire flight window. However, data from the Iridium satellite modem was intermittently delayed depending on the signal quality and server processing delay.

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References


Kazuhisa Fujita
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