COST-EFFECTIVE TELEMETRY, TRACKING AND COMMAND SYSTEM DEVELOPMENT FOR HIGH-ALTITUDE SCIENTIFIC BALLOON.

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Abstract

To fulfill scientific and engineering research objectives of the high-altitude scientific balloon, Telemetry, tracking and command(TT&C) system is indispensable. However, the existing TT&C system is limited in their use by educational institutions that lack the budget due to high costs. Moreover, it is hard to use for researchers who are not an expert in the communication field. In the present work, a TT&C system, having an operational capability at sea and featuring a low-cost, easy to use, and highly compatible with open-source ecosystems, was developed through microcontroller-based amateur radio frequency(RF) module and the Iridium satellite system. The developed TT&C system was verified by multiple actual flight tests. Multiple consecutive flight tests showed reliable connection between the scientific balloon and Ground Station(GS) during its experiment.

1. Introduction

A high-altitude scientific balloon is a stratospheric balloon that is widely used for scientific and engineering research, for instance, atmospheric science, meteorology, and near-space environment experiments. To achieve these scientific and engineering research objectives, telemetry, tracking, and command system (TT&C) is imperative. The telemetry is one-way communication system from the balloon to the Ground station(GS). During its mission, the house-keeping information, such as temperatures, pressures, battery voltages, is transmitted to the GS to monitor the balloon status and anomalies. Tracking system provides the current position, i.e., latitude, longitude and altitude information to the GS via appropriate wireless communication method depends on given circumstances. The command system is used to perform specific actions, such as rope cutter activation for flight termination and ballast valve actuation for the ascent.

Existing TT&C communication systems are expensive to use by educational institutions with a low budget. It has also been difficult to be developed by beginners who do not have professional knowledge of electronics. However, the advent of open source software/hardware such as inexpensive sensors and microcontrollers has lowered the barriers to scientific balloon use for educational research [1].

Considering the flight test environmental conditions of the scientific ballooning in the Republic of Korea, having many inaccessible mountainous terrains and high population density, the ground recovery operation for the separated balloon system could cause the safety concerns. The methodology to address this problem, the sea recovery procedure was established. Therefore, the TT&C systems need to be capable of waterproofing to operate at sea. Moreover, it must float above the sea surface to transmit and receive radio waves reliably after splashdown on the sea. In the present work, TT&C system, having an operational capability at sea and featuring a low-cost, easy to use, and highly compatible with commercial-off-the-shelf

(COTS) electronics and open-source software, was developed to monitor the balloon mission. Moreover, the TT&C system was validated by multiple test flights including sea recovery operation.

2. The TT&C system development

2.1 Design considerations

The scientific balloon TT & C system operating in the sea for the educational purpose has to take into account followings.

(1) Frequency selection for long-distance
(2) Development and operation cost
(3) Waterproofing and floating

2.1.1 Frequency

The frequency band mainly used for the wireless communication module can be divided into Industry-Science-Medical (ISM) band and amateur radio band. The ISM band is widely used in industrial, scientific and medical applications, and has a wide frequency bandwidth of 2.4 GHz, 5 GHz, and so on, enabling high-speed data transmission. However, it may cause interference to other devices when used in high altitude. According to the radio regulations, the usage of the ISM band output devices which is less than 10dBm can be only used for the high altitude balloon. On the other hand, the amateur frequency band is operated by a person or organization as a radio station for hobby or research purposes. When the amateur radio driver's license is held, it can be used within 100W output freely. Since the loss is less as the frequency band is lower in the same given operating distance as in Equation (1) showing free space loss.

$$FSL=20\log_{10}(d)+20\log_{10}(f)+147.55 \qquad (1)$$

Where d is the distance in km, and f is the frequency in MHz.

Therefore, the amateur V/UHF radio band was selected for the radio communication of the scientific balloon. To ensure the reliability of long-distance transmission and reception, the downlink and uplink link margins of the UHF module are analyzed. As a result, as shown in Table 1, good link results are shown at 19 dB or more.

Table 1. Link margin for the telemetry operations.

No.	Parameter	Value
1	On-board Transmitter power	30 dBm
2	Onboard feeder losses	1 dB
3	Onboard antenna gain	2.5 dBi
4	Free space path losses for 300km	134 dB
5	Ground receiver antenna gain	13 dBi
6	Ground receiver feeder losses	1 dB
7	Ground received power (No. 1 – 2 + 3 - 4 + 5 - 6)	-90.5 dBm
8	Ground receiver sensitivity	-110 dBm
9	Link Margin for telemetry (No. 7 - 8)	19.5 dB

(a) Down-Link

No.	Parameter	Value
1	Command Transmitter power	30 dBm
2	Feeder losses	1 dB
3	Transmitter antenna gain	13 dBi
4	Free space path losses for 300km	134 dB
5	Onboard antenna gain	2.5 dBi
6	On-board feeder losses	1 dB
7	On-board received power (No. 1 – 2 + 3 - 4 + 5 - 6)	-90.5 dBm
8	On-board receiver sensitivity	-110 dBm
9	Link Margin for telecommand (No. 7 - 8)	19.5 dB

(b) Up-Link

2.1.2 Development and operation cost

The high altitude scientific balloon research has been explored under the lead of the national research centers since the enormous initial cost for development and operation of the scientific balloon. Thus, the high cost of development and operation for the scientific balloon has been a barrier to entry for an educational institute. However, the high expense of the scientific balloon research could be reduced by employing the rapidly evolving open source hard/software ecosystem. Moreover, development period could be minimized by implementing the COTS products rather than building custom components from scratch. Fig. 1 shows that the COTS products are used for the TT&C system.

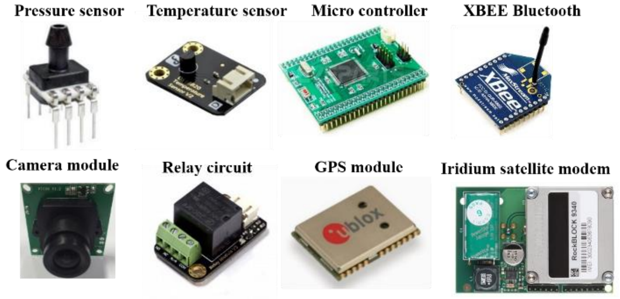

Fig. 1. Commercial off the shelf products

2.1.3 Waterproofing and floating

The TT & C systems operating at sea require watertight and floating functions, unlike that of operating onshore. If a landed gondola is inundated by water, it will not only lose observational data on the gondola, but also the GPS location transmitting electronics enabling the smooth recovery operation will be broken. Also, even if the waterproof function is working properly, if there is no adequate floating equipment for the gondola, it will not be able to communicate with the ground station. Thus, buoyancy management should be taken into consideration carefully. Fig. 2 shows the separation device cutting the suspension line between the envelope and the gondola when flight termination is ordered. Custom-made polystyrene has been implemented to provide buoyancy for floating and to maintain stability to receive radio waves at sea. A most widely used silicon O-ring was implemented for the sealing of the electronics.

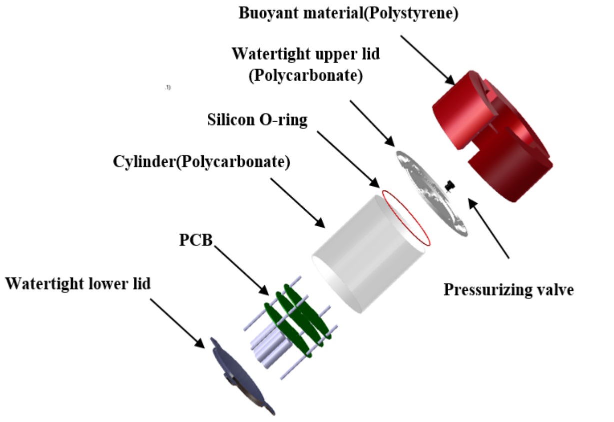

Fig. 2. The exploded view of the separation system.

2.2 Basic onboard package

2.2.1 Communication device

To reduce the development period and make it easy to use for RF novice, a commercially available communication module was implemented for the TT&C system of scientific balloon. A V/UHF transceiver module was used as a primary wireless communication system for the scientific balloon. The UHF transceiver module has both Frequency-Hopping Spread Spectrum (FHSS) and Forward Error Correction (FEC) functions, but the VHF transceiver module has only FEC capability. These features minimize the effect of interference and ensure reliable reception of the status information of the balloon. The detailed specifications are shown in Table 2.

The Iridium satellite communication module which is a low-earth orbit satellite was used as a secondary wireless communication in case of V/UHF RF signal loss with the scientific balloon by various reasons: V/UHF module failure, a blockage of the line–of-sight(LOS) by obstacles such as buildings, mountains.

Iridium satellite communication is SBD (Short Bus Data) type. The maximum size of data available for communication is 340 bytes for transmission and 270 bytes for a reception. Thus, it is pertinent to use for text type status information, not for the image type

Table 2. V/UHF Transceiver specification

	UHF Module	VHF Module
Communication Interface	UART	UART
Air data rate (Maximum)	128Kbps	25Kbps
Sensitivity	-109dBm@64kbps	121dBm@1kbps
Frequency	430MHz	144MHz
Transmitting power	30dBm(1W)	27dBm(500mW)
Features	FHSS (Frequency Hopping Spread Spectrum) FEC (Forward Error Correction) Full-duplex	FEC (Forward Error Correction)

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2.2.2 On-board package

As shown Fig. 3, the TT & C equipment in the gondola system has both the RF and the Iridium module as a redundancy concept in case of the communication failure. It performs the following functions.

1) Data transmission system

The primary communication equipment for monitoring the status of the scientific balloon is a UHF band RF equipment consists of sensors, Mircoro controller unit(MCU) and UHF transceiver. The temperature sensor can measure temperatures as low as -55 degrees Celsius. The pressure sensor uses an absolute pressure gauge that can measure up to vacuum to measure pressures up to 30 km altitude; it is equal to an air density of 1/30 of the ground.

The MCU transmits the measured status information to the ground station at intervals of 15 seconds through the UHF transceiver. Iridium satellite communication equipment was used as a secondary wireless device. It is composed of separate sensors, MCU, and Iridium modem. It

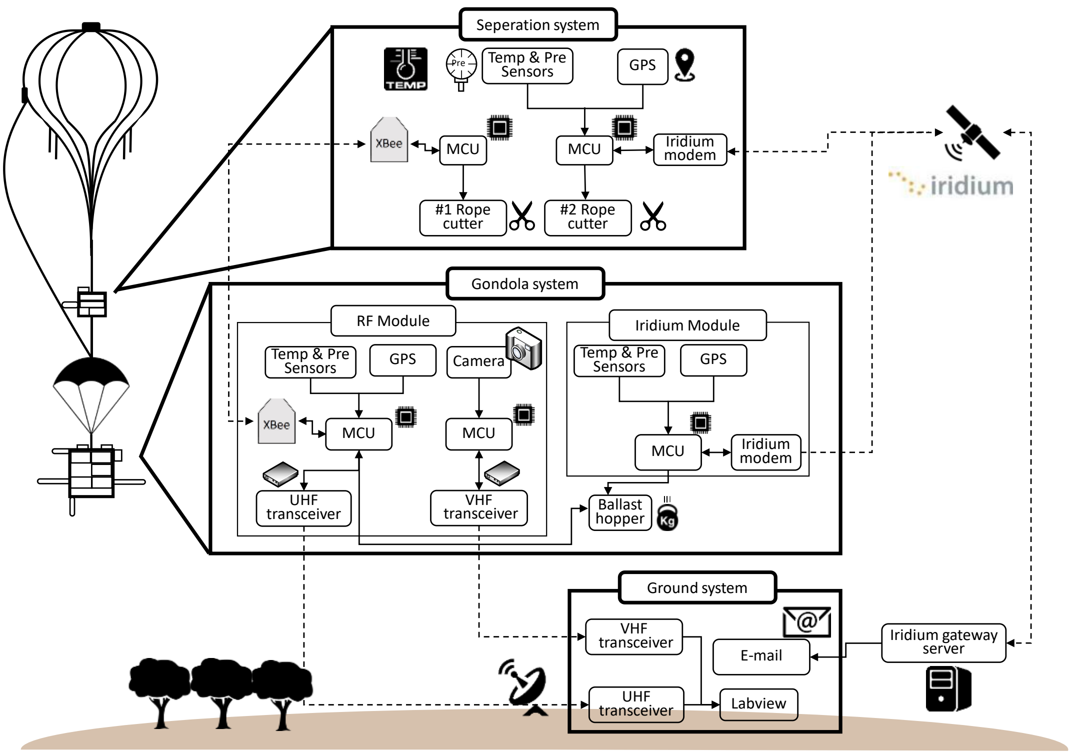


Fig. 3. Block diagram of the Telemetry, Tracking and Command Systems

sends status information of the scientific balloon by e-mail at intervals of 30 seconds.

The VHF band radio device consists of a camera, MCU, and a VHF transceiver is implemented to transmit the still image to the ground station.

The taken images by the Universal asynchronous receiver and transmitter(UART) Transistor-transistor logic(TTL) camera are stored in microSD as JPEG files. The stored pictures are classified into 32 byte packets through MCU command and transmitted to the ground station through VHF transceiver in real time. The time required to receive one 12MB photo was set to one minute. The resolution can be up to VGA (640 × 480). In this study, QVGA (320 Ⅹ 240) grade was used to reduce the transmission time as well as the external visual observation. Fig. 4 is the photograph which was received by the ground station in real time.

Fig. 4. Live streaming still image from the Gondola

2) Locating the scientific balloon

U-blox Neo-6m GPS module was adopted for tracking the scientific balloon. It was installed in UHF RF and Iridium satellite communication system respectively for redundancy. The behavior data of the scientific balloon such as longitude, latitude, altitude and horizontal speed can be obtained in real time.

3) Remote control

The UHF transceiver has a full-duplex function that enables bidirectional communication at the same time. It transmits the status information of the scientific balloon to the ground station while simultaneously receiving the flight termination or ballast control command received from the ground station. The received command signal was decoded to execute the given operation. Then, the MCU operates the # 1 ropecutter mounted on the flight termination system through lightweight, low power Zigbee wireless communication when the flight termination command is received. The solenoid valve is closed by the MCU operation when receiving the ballast control command. Meanwhile, the Iridium satellite communications equipment is complementary to # 2 ropecutter operation and ballast control.

Fig. 5 shows the separation system for flight termination. It has the similar TT & C system as the gondola. The GPS module was used to locate envelope after flight termination. Then, it facilitates the sea recovery operation while saving time. The same temperature and pressure sensors as gondola TT&C system were installed to monitor the behavior of the envelope. That information was transmitted to the ground at intervals of 30 seconds. To reduce battery consumption during long flight mission, communication interval can be adjusted by user's intention.

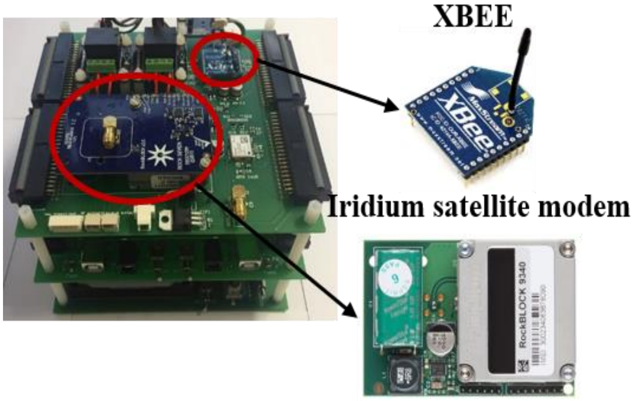


Fig. 5. Electronics of the flight termination system

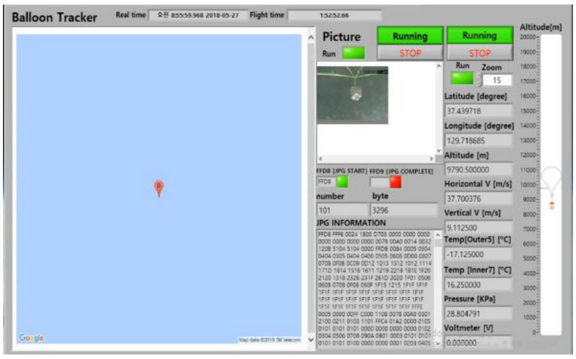
2.3 Ground station package

The developed ground station with V/UHF TT&C system is shown in Fig. 6. It consists of V/UHF Yagi antenna, V/UHF transmitter /receiver module, and Labview GUI program for monitoring the live still image and status information of the scientific balloon. VHF Yagi Antenna A 1.5 m directional antenna with a gain of 9dB receives data from a camera mounted on the instrument. This image data is demodulated through the VHF transceiver module, then displayed on the notebook by the Labview based GUI program.

The UHF Yagi antenna, the 2m directional antenna with a gain of 13dB, receives the status information of the scientific balloon or transmits the control command for given mission. The received status information is demodulated through the UHF transceiver module and then displayed in the status information window of the GUI program.

(a) VHF Yagi antenna

(b) UHF Yagi antenna



(C) GUI for receiving the status information and live still image.

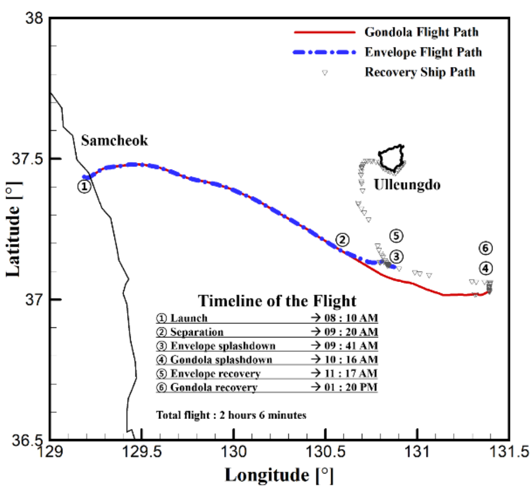
Fig. 6. Developed Ground TT&C system

In case of UHF communication failure, the Iridium satellite system is used as a supplementary device for both command execution and data acquisition. For transmitting the control command from the ground to the balloon for a specific activation, the e-mail attaching the necessary command is forwarded to the Iridium satellite via ground gateway server.

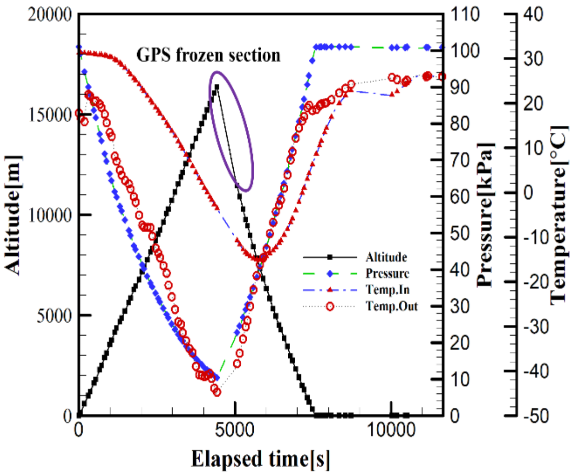
Unlike V/UHF TT & C systems, which require a 2 m long high gain antenna, antenna supporter and cable peripherals, the Iridium satellite systems do not require peripherals. Thus, no space is needed to install supporting equipment and ground stations. It is also convenient to observe the status information of the scientific balloon in near-real time via e-mail from anywhere connected to the Internet after launch. In addition, since the communication is possible all over the world, it is possible to solve the communication disconnection problem in the non-line-of sight situation.

2.4 Flight test results and discussion

To confirm the operational reliability of the developed TT&C system in the sea, four times flight tests were conducted. The flight test data of the zero pressure balloon aiming to reach the altitude 20km with 10kg payload is presented in Fig. 7. The flight test was conducted on 27_{th} May 2018.



(a) Zero pressure balloon trajectory



(b) Altitude, pressure, temperature data

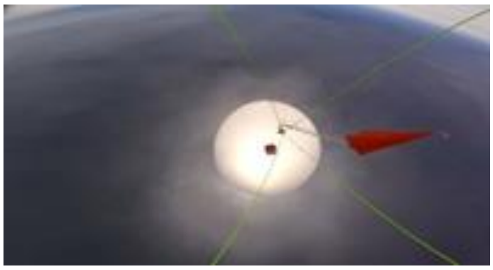
Fig. 7. Zero pressure balloon flight data

Although it was exposed to the low-temperature environment at the maximum of -46 ° C, the ground station continuously received the information of the location including the altitude, the pressure, and the temperature. The flight was terminated 70 minutes after launch to prevent the balloon traveling out of the approved airspace and to reduce the recovery operation time. At the moment of the flight termination, GPS information was frozen for 10 minutes. However, other sensors do not show anomalies. It can be assumed that high acceleration more than the U-blox Neo-6m GPS limitation of acceleration, 4G, was occurred when the parachute deployed. This is called deployment shock of the parachute. The strength of the shock is depended on air density at the time of separation [2]. The lower the altitude, the higher the air density. Therefore, the greater deployment shock of the parachute is incurred at low altitudes. In the case of two flight tests when the rubber balloons ascended to 26 km and then dropped, the GPS stoppage phenomenon was not occurred. This implies that flight termination needs to be executed at or above the 20km altitude where shock strength is approximately 3 ~ 4G to avoid this phenomenon.

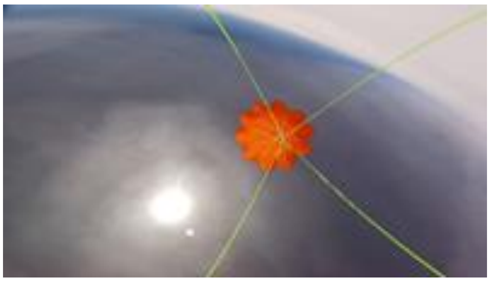
Activation tests for separation part were successfully achieved both the flight termination via remote command and the implementation of the timer function which is separated autonomously after a certain amount of the time elapses. Fig. 8 is sequential pictures showing the deployment of a parachute after the separation device has been activated after receiving a flight termination command.

The fact that the position signals from the Iridium system of both the separation part and the gondola were periodically received for more than 5 hours before the recovery operation is completed demonstrates that the waterproof and floating design has been accomplished.

(a) Before separation



(b) Moment of separation



(c) parachute deployment

Fig. 8 The process of parachute deployment

3. Conclusion

Enormous initial development and operation cost has hindered the entry of the balloon research for the educational purpose. In this paper, a cost-effective TT&C system was developed by employing the swiftly evolving open source software/hardware so as to lower the barrier to entry for the scientific balloon research. This communication system features not only a low-cost, easy to use but also operational capability at sea. Moreover, the TT&C system was validated by multiple test flights including sea recovery operation.

During the flight test, GPS freezing phenomenon had occurred for the first time at 16km altitude, where the air density is large enough to incur more than 4G of the parachute shock deployment. It is recommended that flight termination is performed at an altitude of 20 km or more to prevent this phenomenon.

Through several flight tests, it was confirmed that the separator was reliably operated by command of ground station or by automatic separation function even under low temperature and low-pressure environment. The Iridium satellite communication device was able to periodically transmit position signals even after the splashdown of the envelope and the gondola. That indicates that the waterproof and floating functions were worked successfully.

Therefore, the developed TT&C system proved reliable operational capability at sea and even in the harsh environmental conditions such as low-temperature and low-pressure.

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