# Double balloon configuration for a controlled ascent and descent for atmospheric research.

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**Abstract -** A recently funded AFOSR Multidisciplinary University Research Initiative (MURI), "Integrated Measurement and Modeling Characterization of Stratospheric Turbulence", has embarked on a 5-yr effort to resolve significant operational issues concerning hypersonic vehicle aerothermodynamics, boundary layer stability, and aero-optical propagation. In-situ turbulence measurements along with modeling will quantify spatiotemporal statistics and the dependence of stratospheric turbulence on underlying meteorology to a degree not previously possible. Data from high altitude balloons (HAB) sampling at 1-2 kHz is required to characterize turbulence to the inner-scale, or smaller, over altitudes from 20 km to 35+ km. This poster presents the development of a standard balloon bus, based on reliable commercial-off-the-shelf (COTS) components, that includes radios operating in industrial-scientific-medical (ISM) frequencies with high-gain ground station antennas to achieve data throughputs that potentially enable sub-cm scale sampling. Strategies developed to increase the reliability of conventional latex balloons to achieve altitudes of about 35 km (115 kft) as well as offer controlled descent enabling unperturbed environmental measurements on the downleg are presented.

## I. Introduction

The design of hypersonic vehicles needs to account for the effects of ambient atmospheric turbulence and particles in the middle stratosphere. The lack of statistically significant turbulence measurements at that altitude makes it hard to design the aerodynamics of aircrafts that can consistently fly at hypersonic speeds – above Mach 5 or 3,800 mph- for a long time. Furthermore, availability of such data will enable constraining and parameterizing of detailed modelling.

An AFOSR funded Multidisciplinary University Research Initiative (MURI) "Integrated Measurement and Modeling Characterization of Stratospheric Turbulence"[1] is a 5-year project consisting of a consortium of three universities: University of Colorado Boulder, Embry-Riddle Daytona Beach, and University of Minnesota. High altitude balloon (HAB) reaching 80Kfeet - 120Kfeet will be launched from all three locations

The MURI HAB measurement results will be used for hypersonic boundary layer modeling, aero-optical propagation assessments, and linkages from meteorology to stratospheric turbulence statistics, yielding the following expected outcomes addressing US Air Force capabilities:

- Spatial-temporal statistics of small-scale turbulence in the middle and upper stratosphere, and to what extent are they dictated by larger-scale motions, primarily gravity waves that arise from meteorological sources at lower altitudes.
- Distributions of particles in the stratosphere, and their dependence on underlying meteorology.
- Relative roles of particles and pre-existing atmospheric turbulence for the laminar-turbulent transition at hypersonic speeds in the middle and upper stratosphere.
- Effects of particles, temperature sheets and small-scale turbulence in the middle and upper stratosphere on long-range optical propagation, and how can these effects be accurately represented in computational simulations.

## II. HAB Background and System Requirements

High-altitude balloons are unmanned balloons that are launched into near space with a scientific payload on-board. Filled with helium or hydrogen and expanding as they ascend through Earth's atmosphere, they have been used for climate and meteorological research for more than 100 years, allowing near-continuous measurements from the Earth's surface to about 30 km. However, the sub-cm sampling requirements of the MURI for the analysis, characterization and modeling of stratospheric turbulence are demanding, and fine-tuning of the measurement technique is required to be able to achieve them.

In 2016, Kräuchi et al. [1] proposed two different approaches for data gathering: single-balloon scheme and double-balloon scheme.

In the single-balloon case, the overall payload mass is heavy, and the balloon used was a 7 kg neoprene balloon. It will result in slower ascent rates and longer ascending launches, which will decrease the data throughput and it will impact the overall cost. Moreover, 25% of the launches ends with a pre-mature balloon burst. On the other hand, the proposed double-balloon configuration requires an external system with a structure to maintain the balloons at least 2 m apart to soften the effects of releasing one of them, which complicates the design and the launch setup.

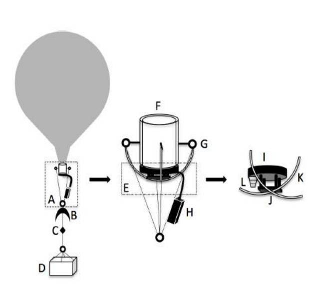


Figure 1. Single-balloon scheme model [1].

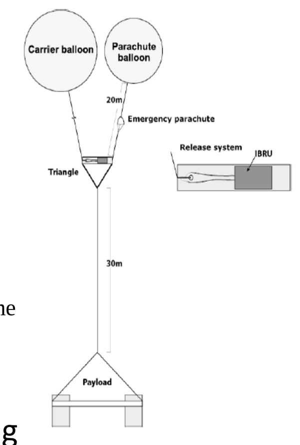



Figure 2. Double-balloon scheme mode [1].

Previous projects and research on HAB allowed for:

- Achieve occasional max altitudes of ~40 km, although the majority of launches reach only 30 km.
- French team launched 94 balloons (sub 1 kg payload on 1200 gm balloons), achieving a mean altitude of 30.5 km +/- 4.2 km (1σ). The minimum was 14.4 km and maximum was 36 km. Only two balloons crossed 35 km.

The MURI High-altitude balloons will carry high data rate sampling instruments on-board. During their flights, real-time data will be transmitted to a ground station that will be tracking them as well as storing the received data for future analysis. The data transmission is required as retrieving of balloons launched from Florida is not practical as majority land in the Atlantic Ocean. Furthermore, the sub-cm scale spatial sampling required by the instruments necessitates high data rate communications, over long range.

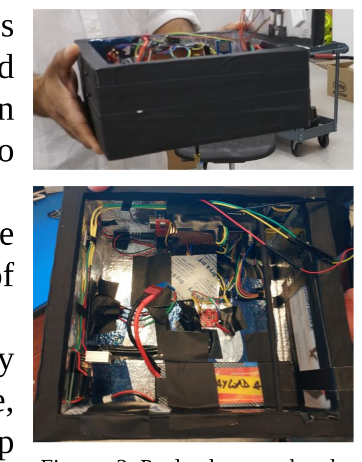
In view of all previous research and the objectives of the project, the following requirements are set to be met:

- Achieve capability for consistent high altitude (~ 35 km) launches.
- Have the ability to 'mass produce' balloon payloads with optimum trade-off between cost and capability to allow more launches for the same cost.
- Conceive a system design for simultaneous multi-point balloon launches and measurements, or multiple follow-on launches for temporal measurements.
- Achieve undisturbed environment for turbulence measurement.
- Achieve high-data rate telemetry for centimeter scale turbulence measurements.

## III. Payload Design

The main components of the design for this HAB payloads are: (1) GPS tracker (2) transceiver (3) on-board sensors (4) on-board computer/microcontroller and (5) flight termination unit (FTU) or controlled descent system.

- **GPS Tracker:** transmits to the microcontroller the NMEA sentences (using a 9k6 bps UART) which contain the HAB coordinates required for the Ground Station (GS) to track the payload. It has a navigation rate up to 5 Hz, a high dynamic range and vertical acceleration up to 50.000 m. Cost: $26
- **Transceiver:** used for housekeeping and sending telemetry data to the GS. It has a 900MHz-1W RF output with a max. data throughput of 115k2 bps. Cost: $99
- **On-board sensors:** generate the housekeeping and science telemetry data. Sensors: internal/external calibrated temperature, low pressure, accelerometer/gyroscope; and voltage dividers. Data gets backed-up in an SD card module. Cost: $35



Figures 3. Payload external and internal design.

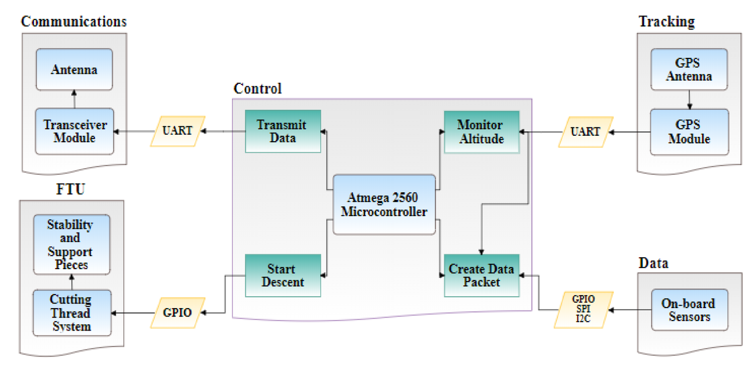



Figure 4 . Payload Design – Block Diagram..

- **Microcontroller:** is the brain of the payload (Atmega2560). It has 4 UARTs, ~50 GPIO pins, SPI and I²C communications, 16 MHz oscillator and low power consumption. It saves permanent data (4 KB EEPROM) and code (256KB Flash mem.). Cost: $25
- **FTU:** heats the resistors to cut the secondary balloon threads. It has two sets of high-current drivers and ¼ W resistors, for redundancy. Cost: $50

The overall cost for one payload is approximately $275.

## IV. Communications Design

The microcontroller fills the transmission buffer of the transceiver to send the packets to the GS transceiver (same model). The transceiver is synchronized with the microcontroller to be able to handle the data packets size and avoid buffer overflows. A transparent protocol is used to broadcast the data for multi-point launches purposes; and using a 230k4 bps UART communication, a data rate (throughput) higher than 100 kbps can be achieved (~102 kbps).

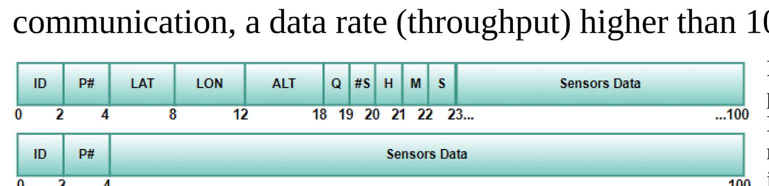



Figure 5. Data packets. Scientific and housekeeping data packets are distinguished by a different packet ID. Housekeeping is sent with the same frequency as the GPS navigation rate (1-5 Hz). All the packets have the same size for implementation and postprocessing simplicity.

To increase the maximum range without loss of communications, the transceiver power output is 1W (30 dBm) and a 5 dBi cloverleaf antenna is used for the transmission. On the GS, a 17 dBi Yagi antenna is used for reception. Cloverleafs antennas have circular polarization, which avoid loss of communication due to polarization mismatches with the linear polarization GS antenna due to payload movement.

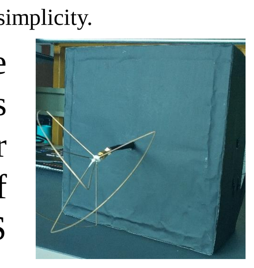


Figure 6. Payload - Cloverleaf antenna.

Considering that the transceivers band is ISM-900MHz, for the highest data rate and a safe link margin, a maximum range of approximately 160-170 km can be achieved

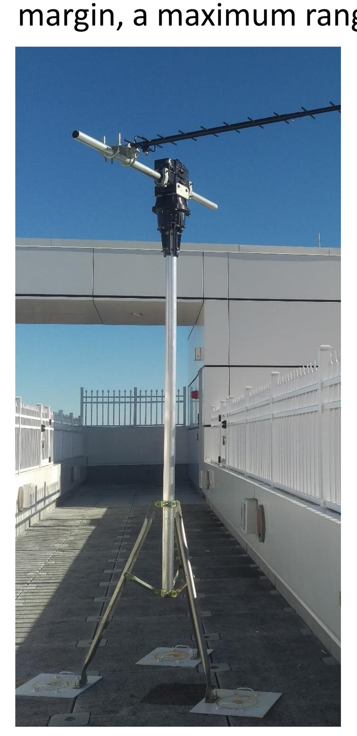


Figure 7. Modular GS: tripod, mast, rotor, antenna.

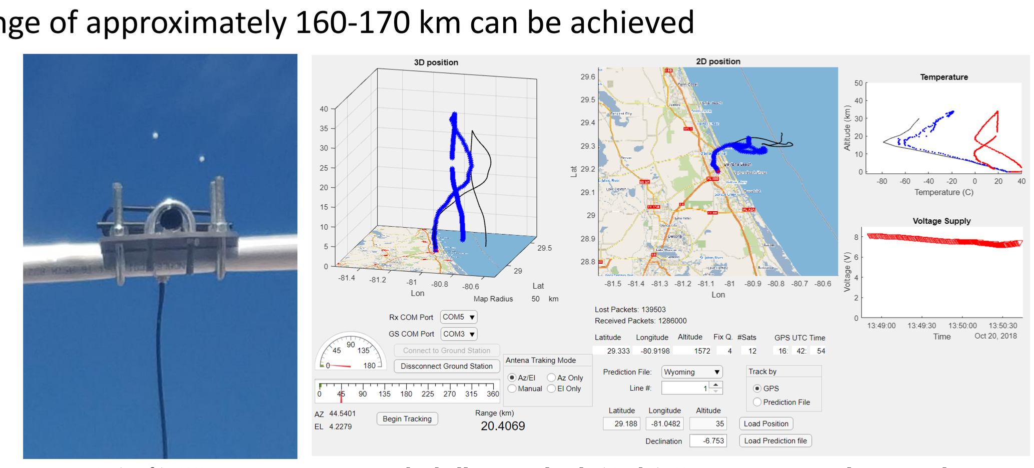



Figure 8. (Left) GS antenna pointing to the balloon payload, (Right) GUI monitoring, plotting and storing data from the HAB payload in real-time.

The launches are monitored in real-time using a graphical user interface that stores the data, presents part of it, and controls the GS pointing control system in real-time. This system uses the GPS coordinates from the housekeeping data packets to point the antenna to the balloon payload. In case of GPS failure, HAB flight path predictors are used to estimate the coordinates to point to the payload.

## V. Controlled Descent Design

The controlled descent is achieved by using a double-balloon configuration. This technique uses a two carrier balloons to lift the payload. When one of the balloons is released, the left one is not able to lift the payload anymore and it starts descending.

Both balloons are attached to the payload with one thread that passes through the support pieces presented in Figure 6. The pieces guide the threads through the specific points that will maintain the payload stability even when one of the balloons is

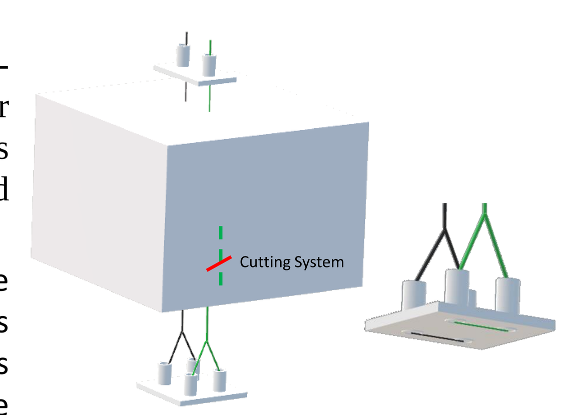



Figure 9. Double-balloon structure 3D model. Connected from the bottom side of the payload to improve stability and cut a single thread inside the payload.

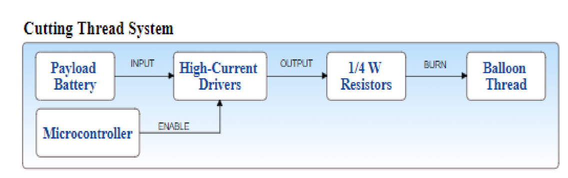



Figure 10. Cutting System Design – Block Diagram.

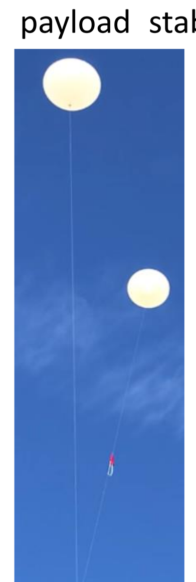


Figure 11. Double-balloon flight model.

That is achieved by placing the support points for the secondary balloon not as close to the payload center as the support points for the descent carrier balloon. The system is activated by the microcontroller through the high-current drivers input enables when the GPS reports an altitude higher than the predefined value. Considering that only a few seconds are required to start descending, the altitude threshold can be assumed to be the maximum altitude that the launch is expected to reach for scientific measurements.

The balloon that will assist the descent is attached to a 1m parachute to make the descent rate even slower. However, this rate will be closely defined by the lift of this balloon.

## VI. Data and Results Analysis

The following graphics were generated with the data gathered from different launches. As it can be seen, a controlled descent increases the vertical resolution of the measurements, improving their quality. The performance of many instruments is worse during rapid free fall through the stratosphere, but a controlled descent makes their data useful.

The range and elevation angle affect the data throughput and the availability of the communications link. Flight predictors were used to determine the best launch window

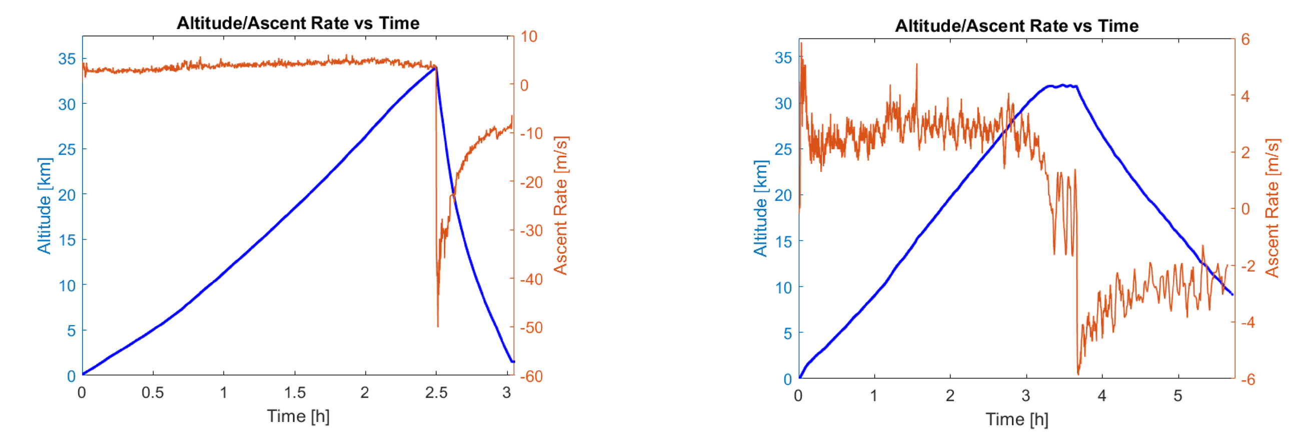



Figure 12. Altitude and ascent rate data during two different launches: (Left) burst of both balloons at ~34 km and descent of approximately 30 minutes at 10-50 m/s with only a 1m parachute, (Right) cutting system activated at 30 km and only one balloon floating before descent of approximately 2 hours at 2-6 m/s .

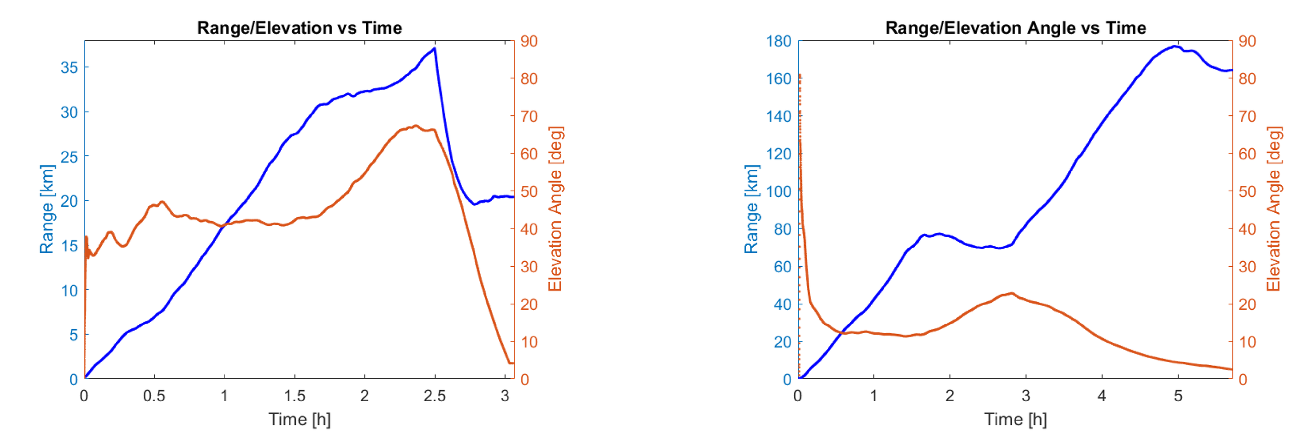



Figure 13. Range and elevation data during two different launches: (Left) range decreasing after 2.5 hours because the payload is descending in the GS direction, and elevation angle rapidly decreasing until GS loses line of sight in less than 30 minutes, (Right) communication link maintained with a range of 178 km from the payload, and elevation angle slowly decreasing until GS loses line of sight in 3 hours.

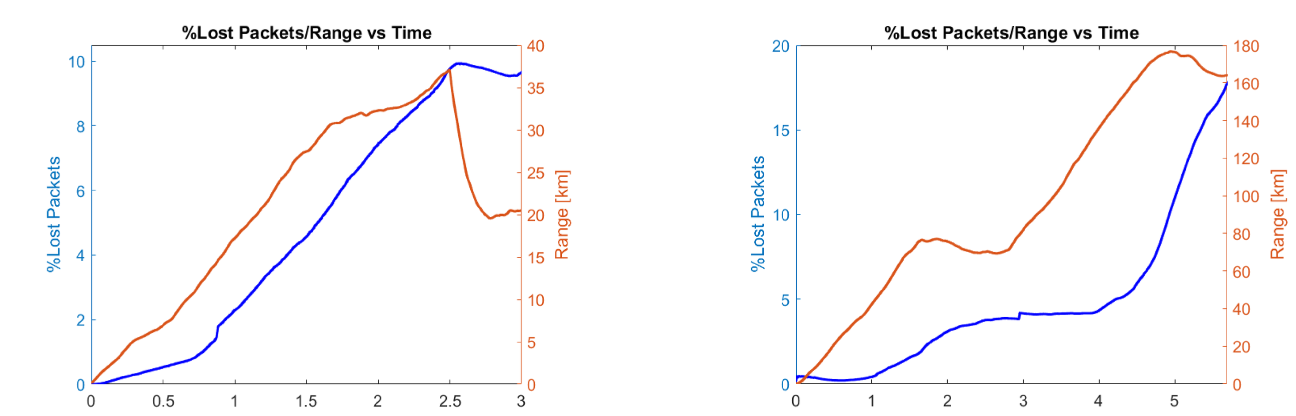



Figure 14. Cumulative percentage of packet losses and range from the payload to the GS during a launch: (Left) 3-hour launch with uncontrolled (parachute) descent with less than 10% of lost packets for a maximum range of 37 km, (Right) 6-hour launch with a controlled descent with less than 18% of lost packets for a maximum range of 178 km. .

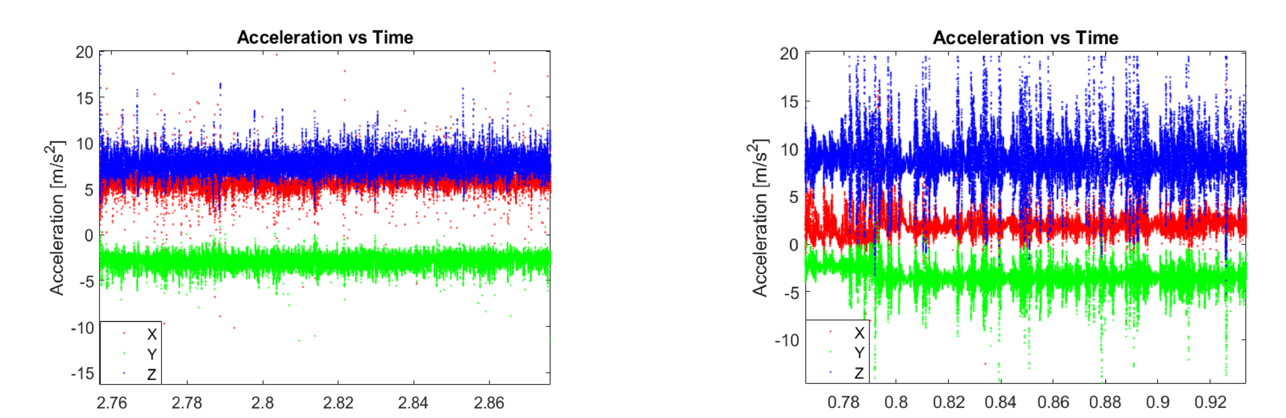



Figure 15 . Acceleration data: (Left) payload descending with one parachute, (Right) payload ascending with two balloons.

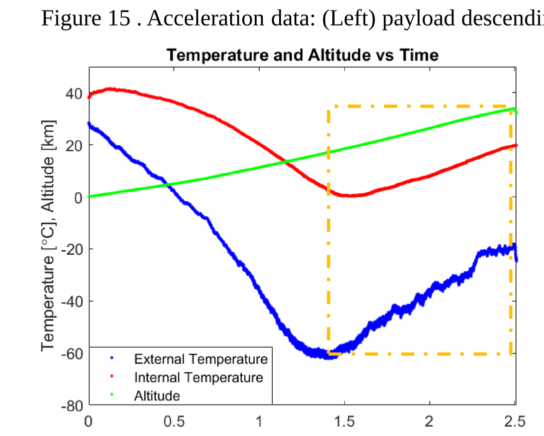



Figure 16. Temperature data: positive internal temperatures, high resolution (~0.1°C) for external temperatures between 20 and +35 km (-65°C, -20 °C).

Figure 14 shows two different behaviors of the payload while flying: a continuous acceleration while the payload is descending and semi-periodic spikes while the balloons are lifting the payload. These representations allow for an analysis in case of loss communication or failure (e.g. cutting system performance) and the progress of the flight.

Figure 15 shows the harsh internal temperatures to which the components are subjected to (monitoring purposes) and the external temperatures for scientific data analysis.

## VII. Summary and future work

The double-balloon configuration design with controlled ascent and descent presented in this poster demonstrate capabilities to be a great candidate for stratosphere parameters measurements for research purposes:

- Altitudes higher than 30 km were achieved (~34 km, currently).
- "Mass production" is possible thanks to the modular design, with a cost per launch of about $750, considering the overall balloon system (e.g balloons, helium, wiring).
- Multi-point and multiple follow-on launches can be accomplished thanks to data broadcasting and modular design.
- High-data rates (~102 kbps, currently) have been validated during the aforementioned tests, which allows centimeter scale turbulence measurements when combined with a controlled descent rate (2-6 m/s).

The data presented is only from sensors that enable design validation. Future launches will include sensors of scientific interest combined with next design steps:

- Single-balloon configuration with air release mechanism attached to the balloon neck.
- Multi-point and launch to increase range capabilities.
- Microcontroller upgrade to improve data collection (data backup) and data throughput.

**References**

[1] A. Krauchi et al, "Controlled weather balloon ascents and descents for atmospheric research and climate monitoring", Atmospheric Measurement Techniques, DOI: 10.5194/amt-9-929-2017, 2016.

[2] I. Leyva and B. Argrow, "Integrated Measurement and Modeling Characterization of Stratospheric Turbulence", AFOSR MURI 2017. [Online] https://community.apan.org/wg/afosr/w/researchareas/22954.

[3] UCAR Center for Science Education, "Layers of Earth's Atmosphere", 2015, [Online]: https://scied.ucar.edu/atmosphere-layers.