EMBRY-RIDDLE Aeronautical University
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Low-Cost High-Altitude Balloon System Configurations with High Data Throughput on a Slow/Controlled Descent

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Abstract - The AFOSR Multidisciplinary University Research Initiative (MURI), "Integrated Measurement and Modeling Characterization of Stratospheric Turbulence", is in the second year of a 5-year 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 sampling at 1-2 kHz is required to characterize turbulence to the inner-scale, or smaller, over altitudes from 20 km to 35+ km. The use of controlled descent systems allows high resolution unperturbed measurements during the descent, while data retransmission out of the altitude range of interest improves the percentage of losses during that part of the launch. This poster presents development of a standard balloon bus and controlled descent units based on COTS components to achieve high telemetry rates that potentially enable sub-cm scale sampling.

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.

This AFOSR MURI 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 24-36 km will be launched from all three locations. Their measurements 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.
- Distributions of particles in the stratosphere.
- Relative roles of particles and atmospheric turbulence for the laminar-turbulent transition at hypersonic speeds in the middle and upper stratosphere.

II. HAB Background and System Requirements

High-altitude balloons have been used for meteorological research for more than 100 years, allowing near-continuous measurements from the Earth's surface into the stratosphere. HABs typically burst around 30 km and the instrument payload descends under a parachute, unless other controlled descent techniques are considered. An undisturbed measurement environment is only achieved during the descent. Descent velocities under a parachuted payload can range from 15 m/s to 60 m/s. Thus, controlled descent mechanism is required.

Kräuchi et al. [1] presented two approaches for controlled descent: single-balloon scheme with a vent mechanism and double-balloon scheme wherein one balloon is cut and descent occurs under the other parachute-balloon combination (Fig 1, 2).

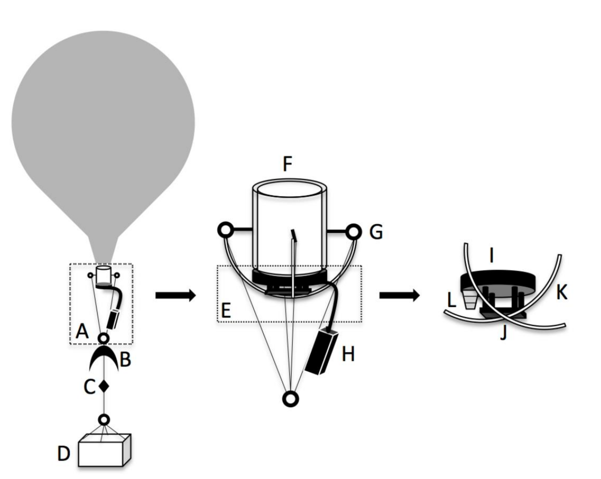

Figure 1. Single-balloon gas vent system [1].

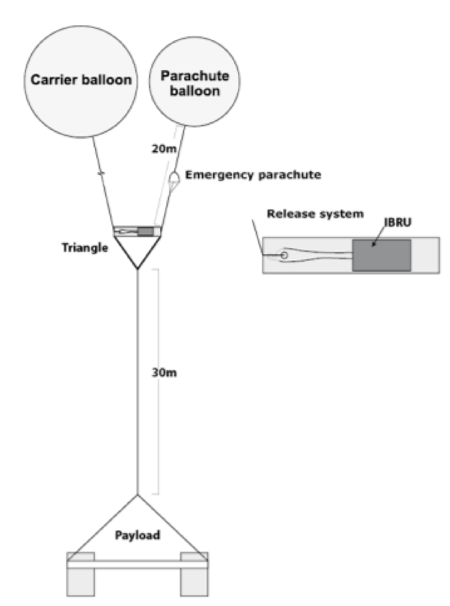

Figure 2. Double-balloon scheme [1].

NOAA did 250 launches of the gas vent system (Fig 1) between 2008-2016, with 75% of balloons reaching 30 km, others burst prematurely. Their double balloon scheme also had similar success rate. In Vignelles [2] the data of 95 launches over 3 years is presented, achieving a mean altitude of 30.5 km +/- 4.2 km, and only two balloons crossing 35 km.

The MURI HAB payloads carry high data rate instruments on-board. HAB systems are usually used as data loggers due to sampling rate requirements and the need of dedicated communications. Their payload is recovered when it lands, relying on commercially available tracking systems, which cannot work in some conditions or locations. During the 95 launches in Vignelles [2], the data was transmitted to a dedicated ground station only 35% of the time to avoid disturbances in the measurements, losing 1.7/5 m of spatial resolution.

For MURI, the payloads transmit data and position in real-time to a ground station that tracks them during the whole launch duration, as retrieving of balloons is not possible for all weather conditions and launch locations. The slow descent techniques necessitates that this communications link maintains a high data throughput over long ranges.

In view of all previous research and the objectives of the project, the MURI project has set itself with the following requirements for the balloon bus:

- Achieve undisturbed environment for turbulence measurements, i.e. slow descent.
- Achieve cheap high-data rate telemetry for centimeter scale turbulence measurements.
- Ability to 'mass produce' balloon payloads with optimum trade-off between low cost and capability to allow more launches for the same cost.
- System design for simultaneous multi-point balloon launches and measurements, or multiple follow-on launches for temporal measurements.
- Achieve capability for consistent high altitude (~ 35 km) launches.

III. Communications Bus Design

Air Segment

The main systems of the MURI HAB payload design are: (1) tracking system (2) communications (3) scientific data/on-board sensors (4) control and (5) data backup and retransmissions.

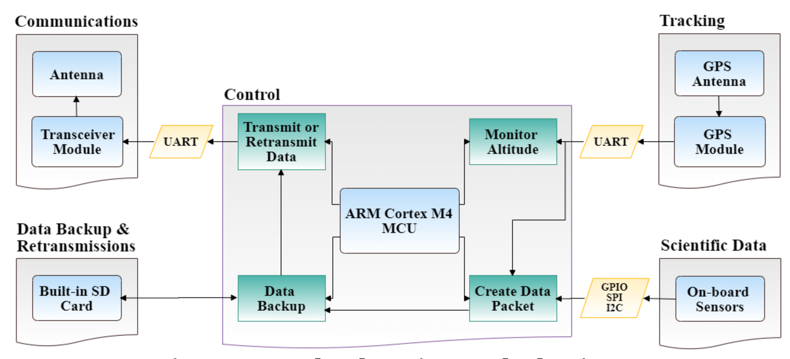

Figure 3. Payload Design – Block Diagram.

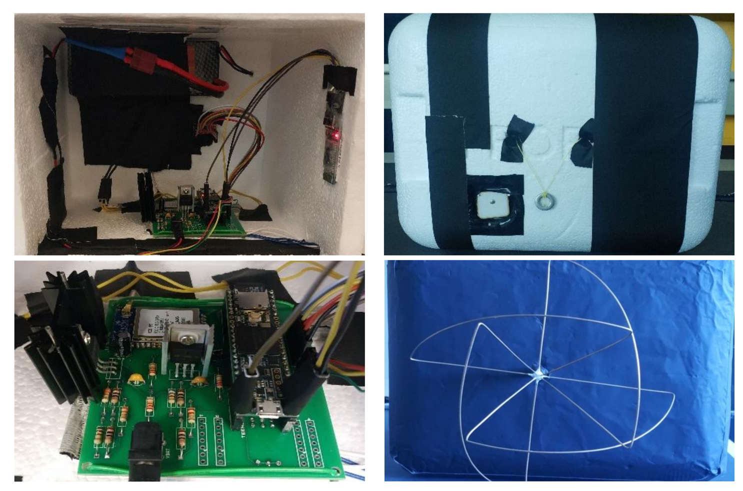

Figure 4. Payload Design. Inside, Top, PCB, bottom.

- **Payload Tracking:** GNSS receiver that computes HAB coordinates for the Ground Station (GS) payload tracking, with navigation rate up to 10 Hz, and maximum working altitude of 50 km. Cost: $26.
- **Communications:** 900 MHz/1W XBee Pro transceiver and cloverleaf antenna used to downlink data to the GS at max. throughput of 115.2kbps. Cost: $105.
- **Scientific Data:** on-board sensors used to generate the housekeeping and science telemetry data. Cost: $35.
- **Data Backup and Retransmissions:** industrial temperature range microSD card. Cost: $11.
- **Control:** Teensy 3.5, 120 Mhz with 62 I/O pins, 6 UARTs, SPI and I2C, and a Floating-Point Unit Cost: $25.

Total payload cost: $265.

Ground Segment

The ground segment consists of a modular ground station and a graphical user interface (GUI). The latter is used to monitor the launches in real-time, perform ground station checks, and reproduce a past launch. The GUI stores the data, presents part of it, and controls the GS pointing in real-time during a HAB launch.

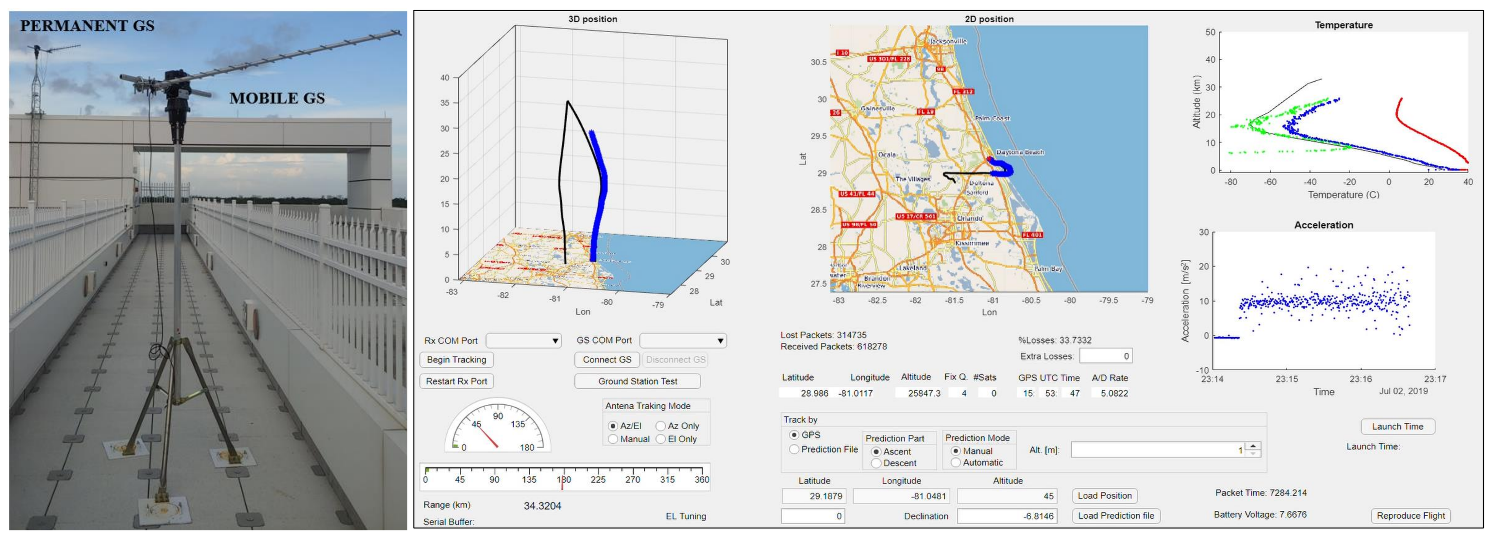

Figure 5 .Ground station: (L) Permanent and mobile modular design, (R) graphical user interface (GUI).

The GS and the payload are configured with the same data packet format. A transparent protocol is used to broadcast the data to one or multiple ground stations (multi-point and multiple follow-on launches).

Considering that the communications band is ISM-900MHz, the design presents a link margin of 8 dB for a slant range of 140 km, achieving data throughputs of ~100 kbps. Higher slant ranges with a low percentage of losses can be achieved if the retransmission of the descent data is considered (+30km – 20 km).

IV. Controlled Descent Systems

To achieve a slow descent, two different designs are considered, based on the same concepts presented in Kräuchi et al. [1]: a cutting thread system and a vent mechanism system.

The main parts of these controlled descent units (CDU) are: (1) controller, (2) temperature monitoring to heat the internal temperature of the system, (3) altitude/time monitoring to determine a threshold to activate the system, (4) descent system based on either a cutting thread of a vent mechanism system and (5) an optional Bluetooth communications system to exchange data with the payload (Fig. 6).

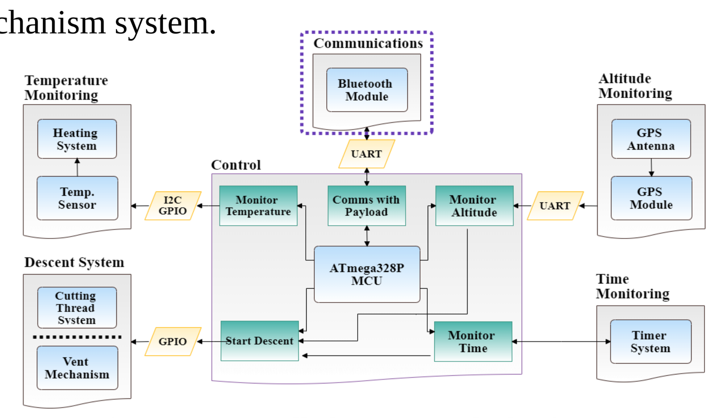

Figure 6. Controlled Descent- Block Diagram.

Cutting Thread System

The controlled descent is achieved by a mechanism based on threads that are attached to low power rated resistors. With high-current drivers, the system controls when to burn the resistors with Figure 7 mechanism.

- **Double Balloon Configuration**

The system is activated based on GPS derived altitude of preset time since turned on. The carrier balloon is cut and released, and the payload descends under an underfilled balloon and a 1m parachute.

- **Single Balloon Configuration**

This design includes a pipe with a cap attached to the neck of the balloon. The cap is retained only by the thread that is cut inside the CDU. The pipe is then open, and a slow descent is achieved by releasing helium from the balloon.

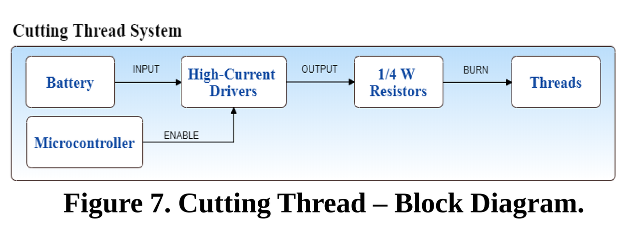

Figure 7. Cutting Thread – Block Diagram.

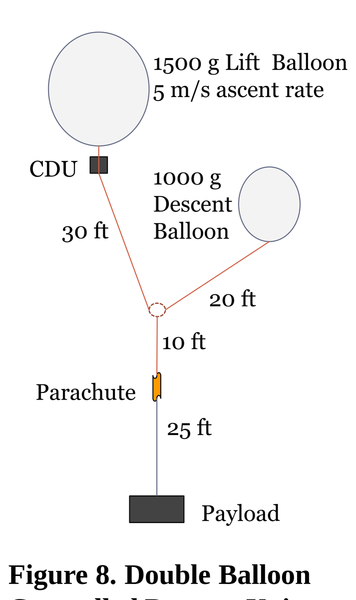

Figure 8. Double Balloon Controlled Descent Unit

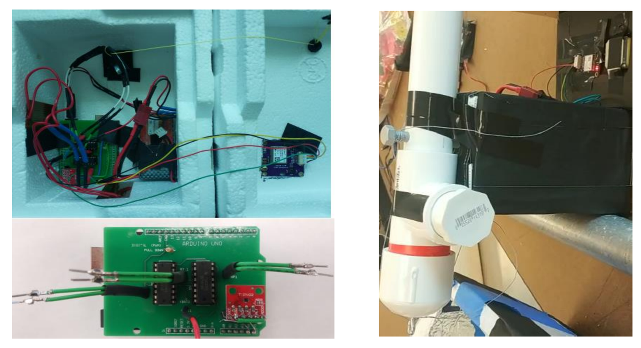

Figure 9. Cutting Thread System: (L) Double, (R) Single Balloon Configurations.

Vent Mechanism System

The CDU includes 2-pieces 3D printed valve that can be opened or closed by a servo motor. The servo motor arm has a thread connected to the valve to control its position. The system can be controlled based on time, altitude, descent rates or by commands being sent from the payload using a Bluetooth communications system.

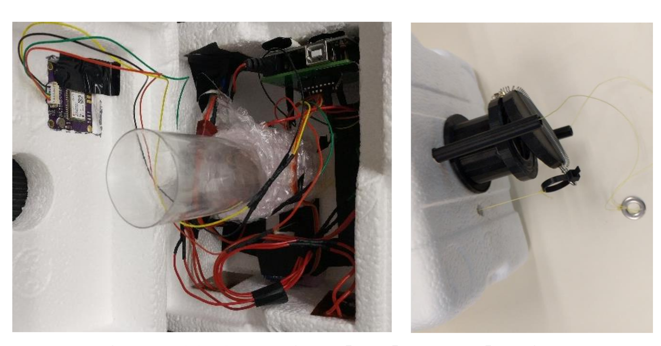

Figure 10. 3D Printed Valve Mechanism

V. Data and Results Analysis

The following graphics were generated with the data gathered from environmental testing and during MURI HAB launches.

The CDU designs were tested in a temperature chamber simulating the flight temperature profile to confirm the correct performance of all the components. As it can be seen, the minimum internal temperature is approximately -15° C when using an internal heating system.

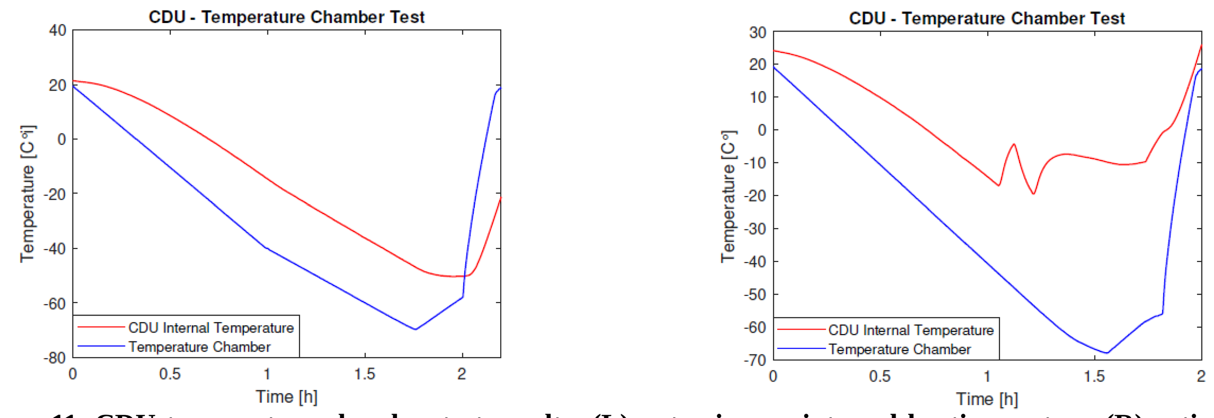

Figure 11. CDU temperature chamber test results: (L) not using an internal heating system, (R) activating the internal heating system when the internal temperature is between -10 and 0° C.

The controlled descent techniques enabled slow descents at rates between 2 and 6 m/s (2-4 m/s 80% time), not possible when relying on only a 1-m parachute supporting the descent.

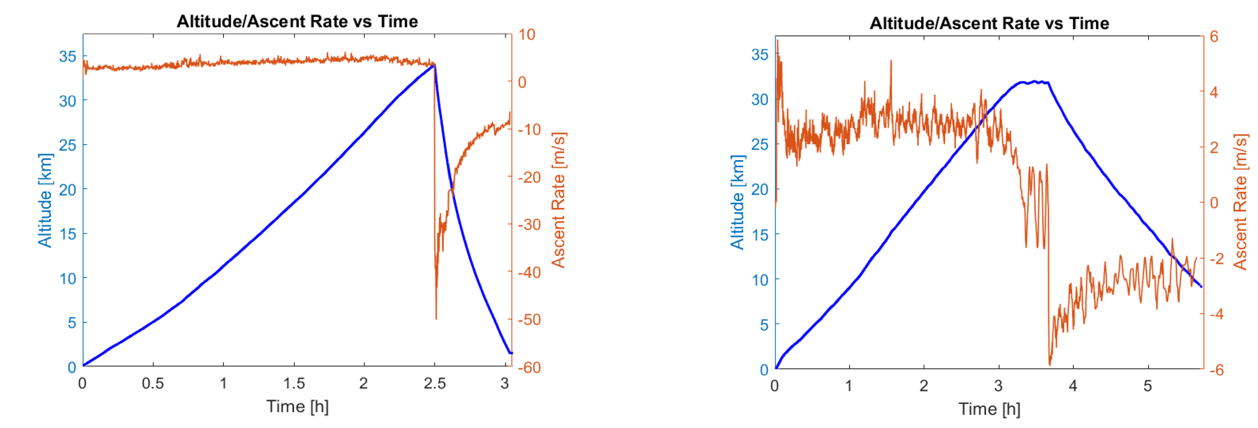

Figure 12. Altitude and ascent rate data: (L) burst of both balloons at ~34 km and descent at 10-50 m/s with only a 1m parachute, (R) CDU activated at 30 km and descent under one balloon at 2-6 m/s .

The retransmissions during the descent improve the overall percentage of data losses.

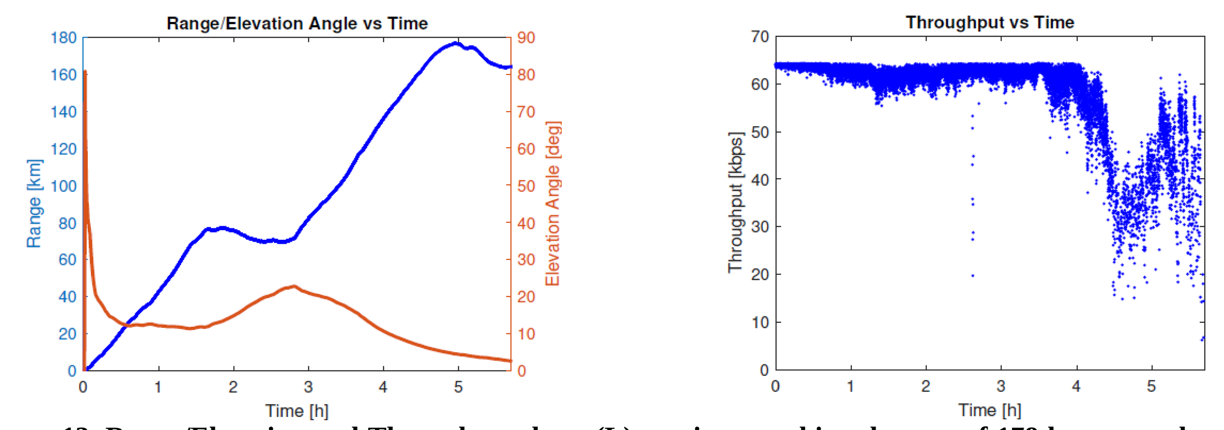

Figure 13. Range/Elevation and Throughput data: (L) maximum achieved range of 178 km at an elevation of 3 degrees, (R) throughput of 62 kbps decreases to ~30 kbps at slant ranges higher than 140 km.

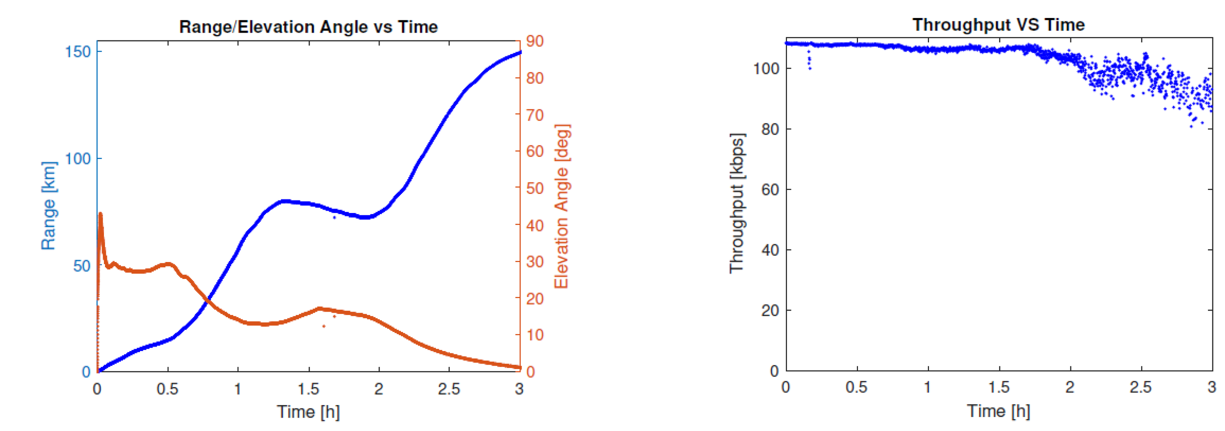

Figure 14. Range/Elevation and Throughput data: (L) maximum range of 150 km at an elevation ≤ 1 degree, (R) throughput of 100 kbps is maintained at slant ranges higher than 140 km using retransmissions.

The multipoint launches and retransmission capabilities of the design were analyzed considering total % of data losses. A single ground station (SISO) system was compared to a 2-ground station (SIMO) system:

- **SISO system:** < 5% of data losses after 3 retransmissions.
- **SIMO system:** <5% of data losses after 2 retransmissions.

Considering a maximum altitude of ~33km and a slow descent, the system shall achieve a low percentage of packet losses in no more than 2 retransmissions. Moreover, a SIMO system enables launches on harsh weather conditions in which slant ranges higher than 250 km are achieved, by using the ground stations as a communications relay.

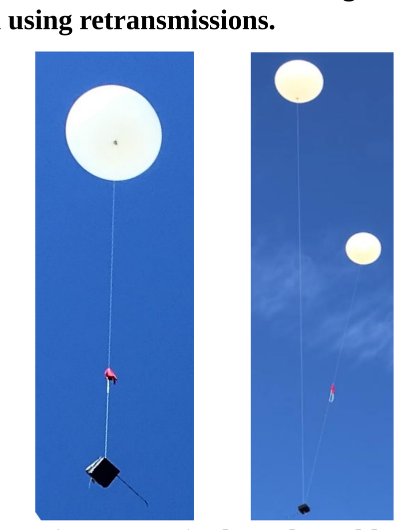

Figure 15. Single and Double-balloon configurations.

VI. Summary and future work

The communications bus and controlled descent unit designs presented in this poster present capabilities to be considered for undisturbed stratosphere and troposphere measurements:

- Altitudes higher than 30 km can be reached for both single and double balloon schemes.
- Slow descents of 3-5 m/s are achieved by using controlled descent mechanism.
- High-data throughputs can be maintained for the whole launch duration, even with slow ascent and descent rates, by retransmitting data of the altitude range of interest during the descent part of the launch.
- System mass production is possible thanks to the modular design, with a cost per launch of $600 and $800 for a single and double balloon configuration, respectively.
- Multi-point and multiple follow-on launches can be accomplished thanks to transceiver capabilities and ground station modular design and cost.

The data presented enable design validation. The final integrated system will include particle and turbulence sensing mechanism used in multipoint and multiple follow-on launches.

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] Damien Vignelles. Caractérisation des performances du nouveau mini compteur de particules LOAC embarqué sous ballon météorologique : application à l'étude de la variabilité spatiale et temporelle des aérosols de la haute troposphère et de la stratosphère. Physique Atmosphérique et Océanique [physics.ao-ph]. Université d'Orléans, 2016. Français. <NNT : 2016ORLE2049>. <tel-01530747>