Chapter 11

# Cost-Effective Platforms for Near-Space Research and Experiments

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.72168

## Abstract

High-altitude balloons (HABs) are commonly used for atmospheric research. In recent years, newly developed platforms and instruments allow to measure position, temperature, radiation, humidity and gas profile in the troposphere and stratosphere. However, current platforms, such as radiosonde, have limited bandwidth and relatively small number of possible sensors on board. Furthermore, all the measuring instruments carried on board the balloon cannot be reused since most of the times the radiosonde cannot be retrieved. In this chapter, we present a generic near-space research platform based on an improved radio frequency (RF) communication, an advanced set of sensors that might also include a return-to-home (RTH) micro-UAV. We present the overall structure of an advanced HAB payload, which is equipped with a low-cost sophisticated set of sensors along with HD camera system, which weight less than 300 g. The payload is tied to a weather balloon with a smart autonomous release mechanism and two-way RF telemetry channel (LoRa or Iridium communication). The payload can be released from the balloon at any given time or position, allowing it to fall at a predicted area. In case the payload is attached to a micro UAV, it can return autonomously by multioptional smart decline to a predefined location using a built-in autopilot. The suggested new strategy is presented using several case studies and field experiments.

**Keywords:** atmospheric and climate research, testing space components, near-space experiments, autonomous near-space flights, high altitude weather balloons, long-range RF communication

# 1. Introduction

## 1.1. Motivation

Traditionally, the space industry was mainly founded by governmental or military organizations. Yet, in recent years, the “new-space” environment attracts several major private companies such as Google, Facebook and OneWeb, each having a large-scale communication project involving global coverage using low earth orbit (LEO) nano-satellite swarm.

The vision of having a reliable and affordable global network, which can be accessed from any location on Earth at any given time, is a challenging scientific task, which attracts both industrial and academic efforts during the last few decades. Currently, the majority of all proposed solutions are based on a network of numerous LEO nano-satellites, which will establish a global network using radio frequency (RF) communication data received on Earth. Major companies such as Google, Qualcomm, Facebook and SpaceX have each invested in similar projects, commonly referred as new-space and near-space projects. OneWeb is one example for such initiative project involving a large constellation of LEO satellites. Other projects such as Google’s Loon or Facebook’s Aquila Drone are not directly focused on satellite constellations but on near-space massive constellation of drones or balloons. The new-space industry includes various small to medium size companies, which are currently developing products for the near-space environment, e.g., Planet Labs and Spire companies are two examples for such effort, which is focused on global imaging and IoT.

Constructing a cost-effective global network requires the use of low-cost electronics, unlike the traditional space industry, which uses dedicated expensive hardware. In order to perform a “space-qualified” testing platform on such components, a flexible modulated testing platform is needed. In this work, we present a new generic methodology for performing near-space experiments based on advanced low-cost payload, which is tied to a weather balloon. The suggested strategy is based on more than dozen balloon-launch experiments encompassing a large number of components (electronics and mechanics), which were tested at 10–30 km heights.

## 1.2. Related scientific work

High-altitude balloon (HAB) platforms have been used for direct atmospheric measurements for more than a century [1]. Measuring devices, which send data from HAB to a base-station located on the ground, using pocket-sized radio frequency (RF) transmitters and are widely known as radiosondes, were first invented by the French scientist Robert Bureau in 1929 [2]. Recently, HAB platforms have started to gain the ability of measuring, recording and transmitting other sources of data from a vast variety of instruments, substantially increasing HAB payload capabilities [3]. Furthermore, the increasing supporting evidence for climate change along with the understanding of real-time atmospheric composition measurements, both in the upper troposphere and lower stratosphere, is a key feature for studying radiative effects in our plant’s climate system [2, 4], emphasizing the need for developing upper-air climate observation platforms [5, 6].

Although the main objective for HAB measurements is to monitor changes in temperature and water vapor vertical profiles in the troposphere and stratosphere, several new upper-air radiation profile measurements indicate supplemental valuable information regarding atmospheric absorption and emission of radiation with respect to the recently revealed interesting insight regarding the radiation obsorbtion/emission dependency with altitude [2]. In addition, due to the fact that our plant's atmosphere is continuously bombarded by energetic particles, mainly galactic cosmic rays (GCR), along with sporadic space weather events, additional particles are introduced into the stratosphere and troposphere [7]. Regardless of this recurring impact, the effects of energetic particles in the troposphere and lower stratosphere are still inadequately understood. There are numerous mechanisms for explaining how weather and climate could potentially be modulated [8], but the majority of energetic particle effects in the lower atmosphere are linked to their potential for ionizing the surrounding air. The formed ions can accumulate on cloud tops, contributing to the microphysics [9], may play a key role in the formation of aerosol (e.g., [10]). In addition, atmospheric ions can absorb directly infrared radiation (IR) [11, 12], and high-energy particles are also presumed to impact lightning rates [13].

Above land and within the boundary layer (~few hundred meters), the atmosphere is mainly ionized by the radiation emitted from radioactive isotopes decay in the Earth's crust [3]. Hess [14] postulated that the ionization profile in the atmosphere should decrease with altitude due to the fact that the radioactive element source is located near the surface. However, after conducting balloon measurements, Hess discovered that the ionization increased at altitudes above 10 km and claimed that it is caused by GCR source. He also determined that penetration depth of these particles depends on the energy spectrum of the incoming radiation [14]. Two decades later, Regener extended Hess' experiments using HAB, measuring ionization rates up to altitudes of 20 km [15]. They discovered that cosmic ray ionization reaches its maximum value between altitudes of 17–24 km and is known as the Regener-Pfotzer maximum (RP max). The Pfotzer Maximum, which is also geomagnetic-latitude dependent [16], formed within the tropopause layer below the stratosphere where primary particles (pions and hadrons) decrease and secondary particles (muons) increase [17]. This is a major source of ionization in the Earth's atmosphere. The establishment of an electromagnetic-muon stream results in ambient air ionization during the release of primary energies by the excitation of air molecules deeper in the atmosphere [17]. During this stream, a portion of the primary particles reach the ground as high-energy secondary particles [18]. The electromagnetic field also interacts with incoming particles, as the sun's solar radiation penetrates the atmosphere. This mixing is directly associated with the pressure decrease as the differential absorption rate within tropopause heights varies [17].

The necessity for developing new techniques and platforms for measuring and identifying energetic ionizing radiation in the atmosphere becomes vital. However, despite numerical model simulations for estimating flight trajectories, high-precision global positioning system (GPS) technology and the relatively slow balloon descent, recovering high-cost payload yet remains challenging, difficult and time-consuming, specifically around mountains or coastal areas [2].

Retrieving the payload enables us to acquire all the recorded data during the flight and that we were not been able to send using wireless communications. This is easier said than done and in practice, HAB payloads are not expected to be retrieved. For retrieving the payload, one should know the exact landing location of the payload, and more important, one must have access to that location. Thus, knowing the payload's exact landing location is not enough as it can "land" in the middle of the ocean or in a high peak of a mountain.

The rest of the paper is structured as follows: in Section 2, we survey the basic principle of flying a high-altitude balloon (HAB). In Section 3, we present design for a disposable cost-effective payload for low-bandwidth applications, which provide the base platform for our experiments. In Section 4, we cover the HAB payload components, power supply behavior, thermal design and pre-flight tests. In Section 5, we present our investigations of long-range communications for low- and high-bandwidth applications. In Section 5, we present our own setup of a near-space return-to-home (RTH) micro-UAV for retrieving the payload with its recorded data. Finally, we discuss our efforts and future work.

## 2. Preliminaries: basic principle of high-altitude balloon

In general, high-altitude balloon (HAB) is composed of the following components:

- A latex balloon—comes in a wide range of weights, which basically reflects its ability to be inflated with helium, common use for HAB may weight 100–1200 g.
- A payload—which includes all the necessary components for conducting the experiment and retrieving the data. In **Figure 1**, two payloads are connected (black and white ice-cream boxes).
- A ground station (GS)—commonly includes an RF receiver. In **Figure 1**, the GS also includes a robotic telescope and transmitter to control the payload detaching process.

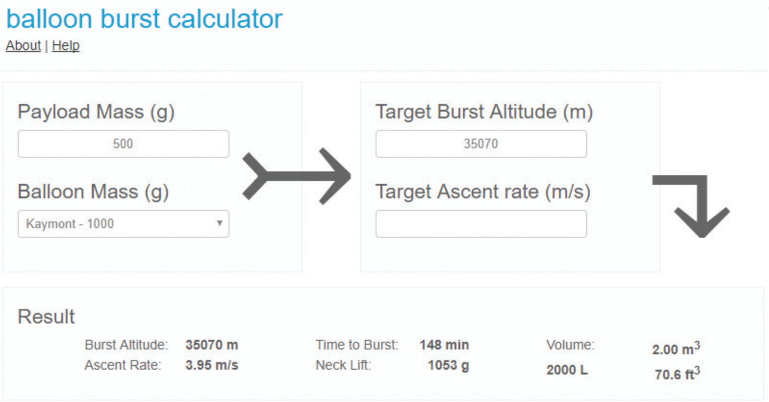
Consider a balloon with a self-weight of 1000 g, about 1000 l of helium is needed in order to allow the balloon to start floating (for each m$^3$ of helium—one can expect a lift of 1000 g—1 kg).

**Figure 1.** Launching a HAB—yet another day at the office.

Assuming 2000 l of helium were used, the 1000-g balloon should gain about 1000 g lift at 1 atm. Assuming a 500 g payload is attached to the balloon, one can expect an overall lift of 500 g. In **Figure 2**, a basic calculation of the expected balloon parameters is presented.

Given the desired requirements for the experiment, e.g., max altitude, payload weight and required floating duration, one can adjust the amount of helium in the balloon accordingly. **Table 1** presents few examples for such adjustment.

As the balloon inclines, its surrounding air pressure decreases. **Table 2** presents the expected air pressure with respect to the balloon height.



Payload Mass (g): 500
Balloon Mass (g): Kaymont - 1000
Target Burst Altitude (m): 35070
Target Ascent rate (m/s):

Result
Burst Altitude: 35070 m
Ascent Rate: 3.95 m/s
Time to Burst: 148 min
Neck Lift: 1053 g
Volume: 2000 L
2.00 m$^3$
70.6 ft$^3$

**Figure 2.** An HAB's lift and burst calculator, from: http://habhub.org/calc/.

| Balloon type | Volume (L) | Payload (g) | Neck (g) | Burst altitude (m) | Ascent rate (m/s) | Duration (m) |
|---|---|---|---|---|---|---|
| 300 Kaymont | 600 | 200 | 316 | 27,890 | 2.96 | 157 |
| 600 Kaymont | 1500 | 200 | 1453 | 29,280 | 5.95 | 82 |
| 1000 Kaymont | 2000 | 500 | 1053 | 35,070 | 3.95 | 148 |
| 1000 Kaymont | 3000 | 1000 | 2080 | 32,135 | 4.84 | 111 |
| 1000 Kaymont | 3000 | 1500 | 2080 | 32,135 | 3.54 | 151 |
| 1000 Kaymont | 4000 | 2000 | 3106 | 30,053 | 4.44 | 113 |

**Table 1.** HAB parameters: Few examples of the lift, duration and burst altitude with respect to the balloon type, payload mass and amount of helium.

| Altitude (m, 15 cel) | Air pressure (atm) | Balloon volume (L) | Balloon diameter (m) |
|---|---|---|---|
| 0 | 1.0 | 1000 | 1.24 |
| 2361 | 0.75 | 1333 | 1.36 |
| 5477 | 0.5 | 2000 | 1.56 |
| 10,278 | 0.25 | 4000 | 1.97 |
| 16,096 | 0.1 | 10,000 | 2.67 |
| 32,230 | 0.01 | 100,000 | 5.76 |
| 48,330 | 0.001 | 1,000,000 | 12.41 |

**Table 2.** Expected air pressure at a given altitude.

## 3. Long-lasting "floating" balloon

In a typical HAB configuration using latex balloon, the balloon will ascend and expand as the air pressure decreases with height due to the thin atmosphere. At a certain point, it will inflate up to its elastic point, explode and fall. This means that if we can make the balloon float in a relatively constant altitude, we can extend its lifespan and endurance. Moreover, fixing the balloon at high altitudes could also enable to test any desired hardware under near-space conditions.

Google's "loon project" is a good example for an HAB setting that is capable of floating up in the atmosphere for a long duration. However, such settings are expensive and complicated, thus they are not a practical solution for scientific researchers.

Our approach for "fixing" the balloon's altitude was directed toward a simple constriction, i.e., a main latex balloon and a cluster of foil balloons. Foil balloons are not elastic and cannot expand, thus their volume can be approximated as constant. This means that as the outer pressure drops due to the thin atmosphere, its upthrust force will weaken and might even change its direction as dictated by the buoyancy force equation:

$$F_B = \left(\rho_{air} - \rho_{gas}\right) gV \tag{1}$$

where $\rho_{air}$ is the surrounding air density, $\rho_{gas}$ is the helium density, $V$ is the balloon volume and $g$ is the gravitational force. We present a basic example of our current test setting design (**Figure 3**):

- A single 1000 g main latex balloon with a capability of 1300 g neck-lift.
- Five non-lasting foil balloons with a fixed volume of about 110 l each, with a self-weight of approximately 90 g. Combining these balloons implies a weight variance of about 500 g.
- A two-parted payload:

**Figure 3.** A long-lasting HAB experiment. This setting retained its floating state for about 2.5 h before the main balloon exploded.

**Figure 4.** The retrieved payloads from the above experiment were found on a distant field, about 100 km from the point of launch. The crashing location was transmitted by the iridium communication system after the crash. In the picture, the upper box is the secondary payload and the main is the lower box.

- Main payload (above) 500-g: Iridium transceiver, GPS, Solar panel, battery, Geiger counter and an autonomous release mechanism for a secondary payload.
- Secondary payload (lower) 400-g: A long-range HD video streaming system based on Wi-Fi and a directional antenna pointing down (14 dBi flat panel antenna).

In this test setting, each foil balloon has a net weight of approximately 0 g on ground level, while the expected weight at an altitude of 10 km is about 70 g. The overall setting provides a lift force of about 400 g on ground level. When reaching to 9–10 km height the system's net lift force should be about 0, making the system relatively altitude-stationary (**Figure 4**).

## 4. Sensors, energy and thermal design

In this subsection, we cover the HAB payload components. First, we present the common needed and used sensors in "near-space" experiments. Then, a brief discussion on energy and thermal design is presented—followed by a discussion of how to test a potential payload (on the ground) for its ability to operate under near-space conditions.

### 4.1. Sensors

- GNSS (e.g., GPS): Global Navigation Satellite Systems refer to a positioning sensor commonly used for computing the 3D position in a typical horizontal accuracy of 2–3 m in the open sky (the vertical accuracy is often not as accurate as the horizontal – errors of 10–20 m are common even in the open sky). We have mostly used U-blox GNSS relievers which are becoming the industry standard for most COTS (Commercial Off-The-Shelf) drones. Remark: one should configure the GNSS receiver to a "balloon-mode" (Airborne) else the positioning might be limited to a low altitude of 12 km or less. Due to the nature of the balloon "Airborne < 1 g" is the preferred model.

Modern GPS can support 10 Hz position sampling rate—yet for most coming measurements, such sampling rate is not needed—as the dynamics of the balloon is very low. Lowering the positioning rate may also help reducing the energy consumption of the GNSS receiver.

- **9DoF**: is basically a set of MEMS sensors: three axis magnetic field, three axis accelerometers, three axis gyroscopes. Combined they can be used to compute orientation. We have used Bosch BNO055 sensor which also has a true orientation filter—and found it both affordable and robust.
- **Barometer**: this sensor measures the atmospheric pressure and temperature. This combination enables us to compute a naïve estimation of elevation in submeter accuracy. However, in our experiments, we noticed that in altitudes higher than 10 km, the barometer's altitude estimation started to slow its elevation in a certain pattern, which repeated itself. Using the GPS sensor measurements, we were able to estimate its true altitude, which consists with the expected altitudes. It should be denoted that although barometers mostly have an elevation accuracy of submeter (in some models subfeet), in high elevation the accuracy gets worse, below is an example of real data of "faulty" barometer (**Figure 5**).
- **Temperature:** thermocouple sensors are simple and robust sensors and being used to measure the inner and outer temperature of the payload. These values are significant for the proper operation of the electronic components and the batteries.

### 4.2. Energy and thermal design

It should be noted that performance of all batteries drops drastically at low temperatures starting −10°C. At high elevation such as 10–30 km the outer temperature is expected to be

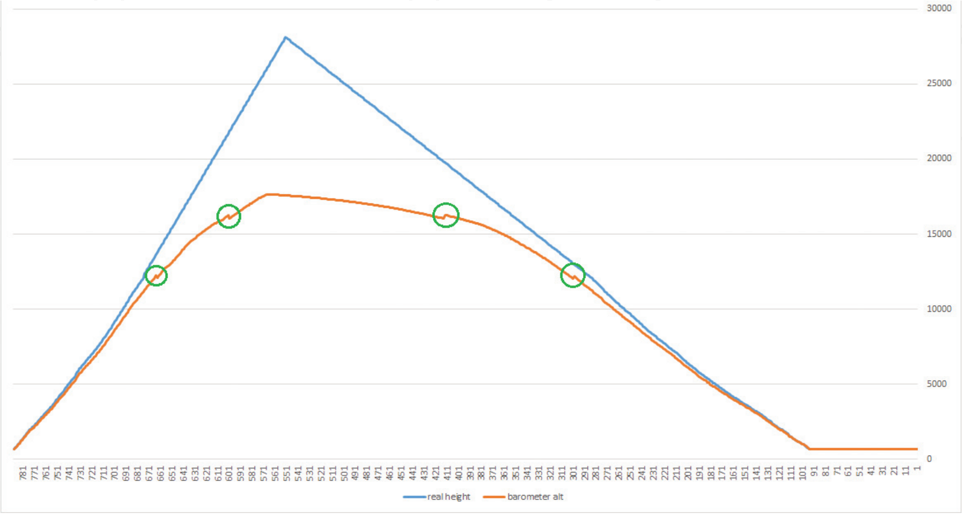


**Figure 5.** The balloon altitude over time, as recorded by the barometer sensor and our true altitude estimation.

[−60–45]°C, respectively. This makes the task of keeping the payload at "room level" temperature (i.e., [0, 45]°C) vital. Packaging the payload with COTS boxes made from materials that provide proper thermal insulation such as expanded polystyrene (EPS) is sufficient for such need. Recall that in height of 16 km, the expected air pressure is 0.1 atm, while at 31 km, it is about 0.01 atm, so air-based passive cooling is significantly less efficient than on the ground.

In practice: taking into an account the above considerations and the fact that most IoT components are suited for operating in near-space conditions it is easy to construct a thermal-balanced payload. Most of the required tests for the payload performances under near-space conditions can be performed with a simple setup, which consists of a vacuum chamber, a home freezer and a simple thermal camera (**Figure 6**). **Table 3** depicts a thermal analysis of a Samsung Galaxy S6 mainboard under low ventilation conditions.

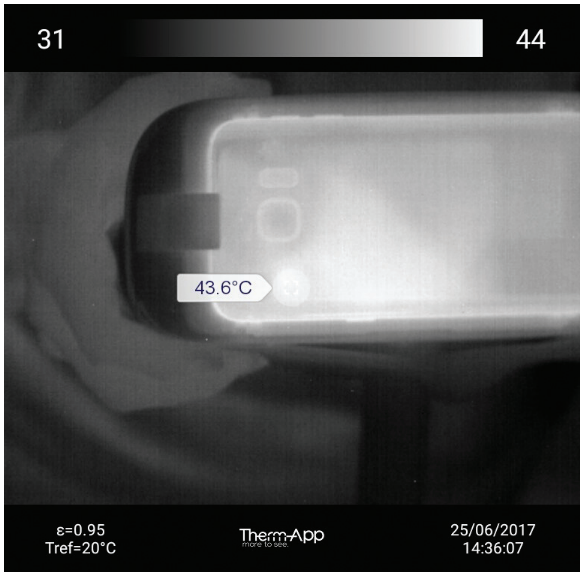


**Figure 6.** Thermal analysis of an android phone using a thermal camera (Op-gal's Therm-app).

| Platform | Max altitude [m] | Max horizontal velocity [m/s] | Max vertical velocity [m/s] | Sanity check type | Max position deviation |
|---|---|---|---|---|---|
| Portable | 12,000 | 310 | 50 | Altitude and velocity | Medium |
| Stationary | 9000 | 10 | 6 | Altitude and velocity | Small |
| Pedestrian | 9000 | 30 | 20 | Altitude and velocity | Small |
| Automotive | 6000 | 100 | 15 | Altitude and velocity | Medium |
| At sea | 500 | 25 | 5 | Altitude and velocity | Medium |
| Airborne <1 g | 50,000 | 100 | 100 | Altitude | Large |
| Airborne <2 g | 50,000 | 250 | 100 | Altitude | Large |
| Airborne <4 g | 50,000 | 500 | 100 | Altitude | Large |
| Wrist | 9000 | 30 | 20 | Altitude and velocity | Medium |

**Table 3.** Form: U-blox M8 N manual—make sure you use airborne mod (the default is portable—so the GPS will not work above 12 km).

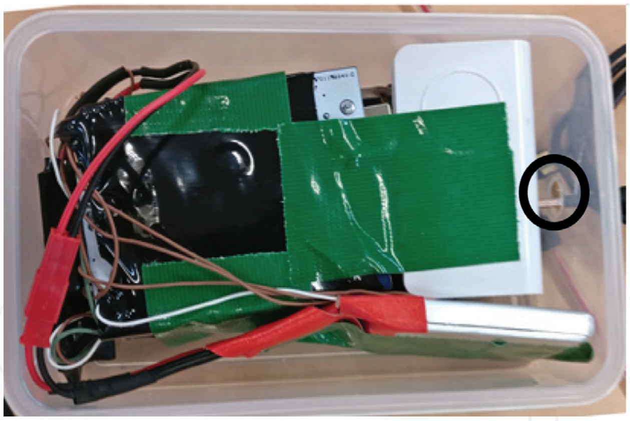


**Figure 7.** A typical thermal-balanced-payload, notice the ventilation hole marked with a circle.

A typical payload will include a GPS, microcontroller, LoRa modem, Geiger counter, barometer and humidity sensor (**Figure 5**). The total energy consumption is about 250 mW (**Figure 7**).

## 5. Disposable cost-effective payload for low-bandwidth sensor data applications

In most cases, we usually direct our efforts toward recording and transmitting low-bandwidth sensor data or testing electronics at near-space conditions. As retrieving the payload with its data is not always certain, we designed the payload to be cost-effective and disposable and yet capable of long-range low-bandwidth communications.

Our basic HAB payload setup typically includes the following components:

- Arduino MCU.
- 433 MHz LoRa radio transceiver.
- Versatile GNSS module capable of GPS, GLONASS.
- Environment conditions sensors (barometric pressure/altitude/temperature/humidity/Dewpoint).
- An actuator for releasing the payload on command.
- Geiger counter-based on the new solid-state technology (which reduces the weight and price of Geiger counter).

Such payload's BOM (Bill of Material) will cost about 100–120$. The weight of the payload can be reduced to a sum of 150 g, making it suitable for 300 g HAB. The total cost including the cost of the launch will cost less than 200$. In case there is no need for a Geiger counter, the overall BOM of the payload and balloon can be below 100$.

Using this affordable payload design, we were able to perform several experiments in which we measured Gamma counts with respect to altitude and location in relative high accuracy. **Figure 8** shows the real-time Geiger count as received at the GS from the payload (over 120 km range).

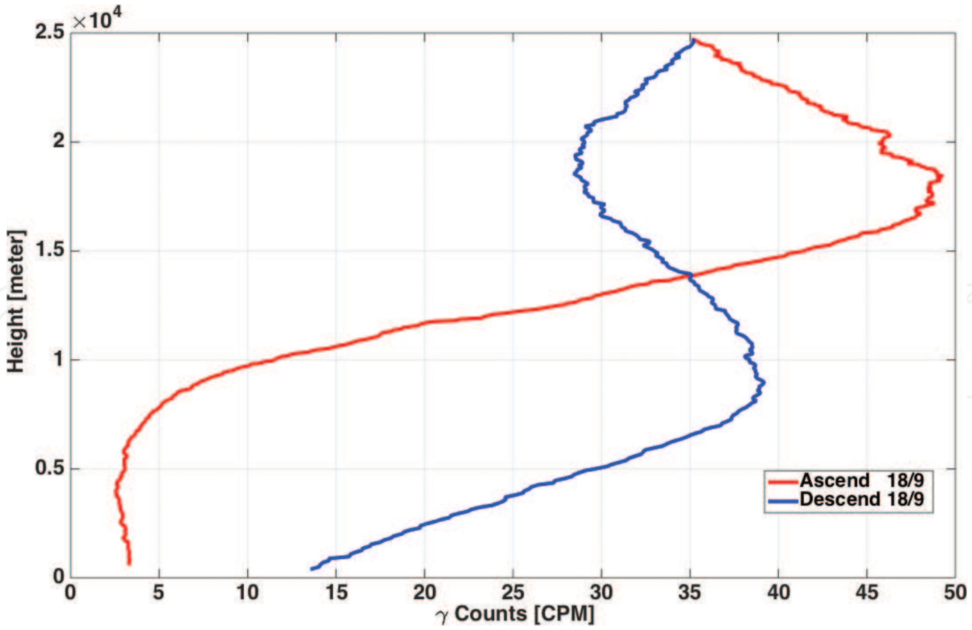


**Figure 8.** Gamma count vs. altitude.

## 6. Long-range communications

### 6.1. Current state

Radiosonde is the most common type of payload which is capable of long-range communications suitable for HAB. A radiosonde can be regarded as a black-box which includes a variety of sensors and a radio transmitter. Radiosondes may come in various shapes and technologies, but in general, they measure: position (GPS), barometric pressure, humidity and temperature. They also may include some other related sensors such as Ozone meter. These data are transmitted to the GS using RF communications, commonly—UHF 400–406 MHz, and 1675–1700 MHz. This solution's range is typically between 50 and 200 km that depends on environmental conditions.

As mentioned above, radiosonde payloads are closed systems that limit the user's ability to customize them. This means that in order to transmit additional sensors data, an additional communication device is required as well. Moreover, they provide low-bandwidth and half-duplex (download only) communications. It should be noted that the RF, which is used by a radiosonde, is not an ISM band, and therefore, it might require RF approval by local authorities. Other concerns about using radiosonde communication abilities include the lack of frequency reusability and security in most Radiosonde payloads.

Providing high-bandwidth communications enable us to obtain real-time measurements such as multi-spectral images and conducting high-resolution gamma-ray spectrometer measurements. Full-duplex communications enable us to interact with the payload, so we can remotely control the payload or the balloon motion. The ability to adapt the modem communications setting, i.e., reprogramming it in real-time makes it a more flexible solution that provides bandwidth and range according to the user's needs or environmental conditions. In our experiments, we consider the minimally required coverage range to be about 40–50 km that is required for conducting HAB missions.

Cellular 3G/LTE communications are intuitively a natural solution for full-duplex and high-bandwidth communications that is communally used by “makers”. However, a cellular device that has been used at high altitudes can be easily detected by multiple base-stations simultaneously. Generally, such device will be blocked by the cellular providers thus making its 3G/LTE communications inoperable till the device returns to ground level.

This makes smartphones not suitable as a real-time communications solution for high altitudes. On the other hand, for low altitude applications or when it is known that the payload will fall in a cellular covered area, smartphones might be considered as a suitable communication solution. Denote that in many countries (e.g., USA) mobile phones are required to operate in “flight mode” while “in-air”.

UHF RF communication such as 433, 866, and 915 MHz which are ISM RF bands can provide low-bandwidth and long-range communications solution. We have investigated many drones remote control (RC) two-way communication solutions, and we found that while they can provide long-range communications their high-energy consumption and cost make them less appealing for day-to-day HAB missions. As an example, the DragonLink RC technology, which is the gold standard for flying long-range drone’s communications, required in our experiments 1.5 W transmitter for achieving the range of 40 km and a data rate of 19.2 kbps.

In our experiments, we found that LoRa technology-based devices are the most suitable and preferable solution for HAB missions’ requirements. Meaning, they are robust, programmable, with a very low-energy consumption and affordable. With the right setting, we were able to achieve full-duplex communications with a 25 mW transmitter more than 120 km range and a data rate of 0.4 kbps.

Wi-Fi technology can provide high-bandwidth communications, however it was designed for as Wireless Local Area Network (WLAN). This means that with COTS hardware in a direct line of sight communications, its expected range is limited to hundreds of meters. We have designed a long-range Wi-Fi setting based on EZ-WiFiBroadcast settings. EZ-WiFiBroadcast is a special DIY design of Wi-Fi communications which is commonly used as a poor man’s long-range HD FPV solution. With our current long-range Wi-Fi setting, we have been able to capture 720P video from a HAB at 9.8 km height and located about 15 km from the GS.

Free-Space Optical (FSO) also known as laser communications are a less common high-bandwidth communication solution which can be achieved by the use of a robotic telescope which tracks in real-time the HAB. In a clear day, such device can track an HAB for over 50 km. In our experiments, we successfully tracked HABs for more than 70 km using low-cost Celestron StarBright XLT telescope with 127 mm aperture Schmidt-Cassegrain lens. As shown recently by Google in their Loon project “Demonstration of free-space optical communication for long-range data links between balloons on Project Loon”. This kind of high-bandwidth communications is still extremely complicated and requires technical skills and efforts which are not common in most research groups.

Another commercial solution is Global satellite communications (we have used Iridium’s two-way Short Burst Data—SBD), this kind of solution requires a “pay per message” data plan

(~10 cents per 50 bytes)—so it is applicable for low-bandwidth missions. Yet it allows full control, two-way communication. Another satellite-related solution named "SPOT" is commonly used to track HABs. This one-way (transmission only) solution uses the "Global-Star" satellite network for near global coverage. Interestingly, we have found that the use of short message service (SMS) in cellular communications was relatively efficient and we were able to send and receive text messages from about 5000 m height when the expected height is about 2500 m.

### 6.2. Cellular 3G/LTE communications

In this section, we present methods for constructing simple (DIY) payloads based on COTS devices. We start by presenting a naive attempt to shoot high-resolution images from high altitude—as part of a class challenge in the undergraduate "Autonomous Robotics" course during the year 2017 (given in the Computer Science Department at Ariel University). All suggested solutions included an Android phone with an international sim card and an app which captures time-laps photos with position while attempting to upload them using existing cloud uploader tools (**Figure 9**). The balloon launches included the following setting:

- A regular latex 600, 1000 g balloon.
- Smartphone-based payload—100–200 g. Android phones with the needed apps for time-lapse camera (such as OpenCamera) and a cloud-based uploader app (such as Dropbox or Google drive). The phone was equipped with a sim card which can be used for uploading the data—using a prepaid data plan.
- Thermal Box: the most common is polystyrene (ice-cream box)—which is needed to maintain a controlled temperature for the phone electronics and batteries.

Five different solutions were implemented (see **Figure 10**) mainly using the OpenCamera android open source. None of the payloads could capture reasonable images from high altitude

**Figure 9.** Three payloads ready to be launched—each with a smartphone and software for uploading the gathered data. As part of the navigation graduated course in Ariel University (Israel). None of the payloads could actually transmit good and clear images from high altitude. All payloads eventually fall in Suraya. Over 200 km from launch.

—although at least three (out of five) phones made it back safely to the ground and two of them even sent few images—until it was discovered by a "lucky founder" or simply run out of power.

Although the suggested concept failed the overall solution of using a software-only solution based on affordable smartphones seems to be a feasible cost-effective solution to many near-space applications.

### 6.3. Long-range Wi-Fi communications

Long-range and high-bandwidth communication solutions suitable for HAB missions are not common, especially not as COTS hardware. High-bandwidth data applications such as multi-spectral imagery or high-resolution measurements have a great value for exploring various electrical phenomena such as lightening discharges, sprites or blue-jets in the atmosphere and other aspects of this environment.

For providing high-bandwidth communication capabilities, we are directing our efforts on utilizing COTS communications hardware based on IEEE 802.11 standard WLAN which is also known as Wi-Fi. Wi-Fi networks can easily provide high-bandwidth communications but with COTS hardware they have a very limited range. Using a much more sophisticated hardware can extend its range dramatically to a few kilometers, but such systems are costly, with high-power demands and with a form factor that is not suited for a typical HAB's payload (**Figure 11**).

In theory, the use of a high gain directional antenna about 18–24 dBi for the receiver at the ground station and a directional antenna with a gain of about 10–14 dBi should provide us a link budget greater than 150 dB. Such link budget should enable communications for long ranges estimated at 10–30 km on regular conditions. In optimal conditions and a Forward Error Correction (FEC) mechanism, the range can be extended to about 50 km (**Figure 12**).

This lead us to investigate a different approach that uses COTS Wi-Fi hardware but in a non-traditional way. Some of the IEEE 802.11 network interfaces can operate in a special debug

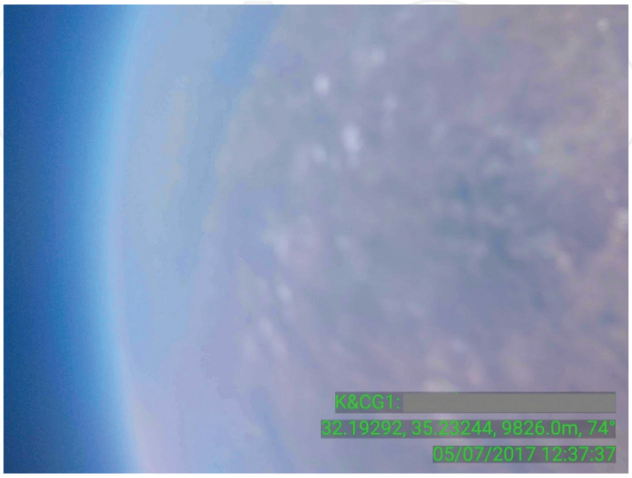


**Figure 10.** An image of the sky that was made by an android smartphone (Xiaomi Redmi 4A). In this experiment, the phone's camera was out of focus. It might be due to ice on the camera lens. The images were successfully uploaded after the payload has made it to the ground.

**Figure 11.** HAB ground station (GS): Left: The GS in general: two robotic telescopes with (auto-track) and a high gain 24dBi Wi-Fi antenna. Right: the robotic telescope: (a) A view-finder webcam. (b) A Wi-Fi + 3G router. So the telescope can be controlled globally. (c) A Pi-camera mounted to the telescope eye-view. (d) A Raspberry Pi which controls the telescope using either visual tracking and GPS coordinates.

**Figure 12.** Keep it simple: launching two simple payloads: Raspberry-Pi (upper) and an android smartphone (taking this image).

mode that allows them to transmit and receive Wi-Fi communications with no regards to the IEEE 802.11 standard itself. As such, "makers" have used this feature for creating a "poor man's" long-range HD FPV solution. We based our system on "bortek"'s version of EZ-WiFiBroadcast (**Figure 13**).

Typically, the Wi-Fi long-range system includes:

- Raspberry-Pi (RPi) device usually Raspberry Pi 0, with RPi-Cam camera and a Wi-Fi Network Interface Card (NIC) with an external directional 14 dBi flat panel antenna with its face directed down.
- Ground station based on another RPi device with an external 20 dBi directional antenna.

Even though that our research on this approach is at early stages we have been able already to capture 720P video from a HAB at 9.8 km height and in an estimated distance of about 15 km with our long-range Wi-Fi communication system. **Figure 13** is an image captured in this particular HAB mission. We found that flat directional antennas perform quite well as long as the angle between the balloon and the GS was not too wide.

As the GS design is compact it can be used as a mobile ground station located on top of a car which "chases" the balloon.

### 6.4. Long-range communication LoRa vs. iridium

In Europe, there is a well-established RF solution for tracking on HABs led by the UK High Altitude Society (https://ukhas.org.uk). This cooperative solution allows an online tracking mechanism based on COTS Software Defined Radio (SDR). This system is based on a fixed low-bandwidth protocol—mostly at the 434.075 MHz frequency and has been successfully in use for hundreds of launches annually. Yet, in many cases the UKHAS system is not suitable due to geo-location, bandwidth or even security reasons. In this work, we mainly focus on such cases in which a "real" Ground Station is needed. The iridium modem allows true global coverage and two-way communication, yet it is relatively expensive (300$) and requires a data plan which cost about 2$ for kB (a compressed single JPG image of 100 kB—will cost about 200$). This kind of pricing makes it applicable mainly for strictly low bit rate application. The LoRa modem is an affordable (10–20$) system with adaptive bit rate and works in unlessens band. The expected range for LoRa communications is over 120 km, while in a few places around the world, LoRa gateways are started to be deployed so that the expected route can be covered. But in general even with a single LoRa gateway it is expected to cover the balloon route (50–200 km)—using a standard UHF Yagi antenna in the expected range. We conclude that the LoRa solution can be an affordable complementary communication solution. It can be connected to a smartphone allowing long-range communications coverage and with actively connected to the Iridium system it can benefit the most to the satellite communication (**Figure 14**).

```
-72dBm
Rx0(A): -72dBm (2226304)
Starting RX ... (FEC: 8/4/1400)
```

**Figure 13.** The smartphone payload shot from an upper payload based on a Raspberry-Pi camera equipped with a long-range Wi-Fi transmitter. The picture was taken at about 9.7 km above ground.

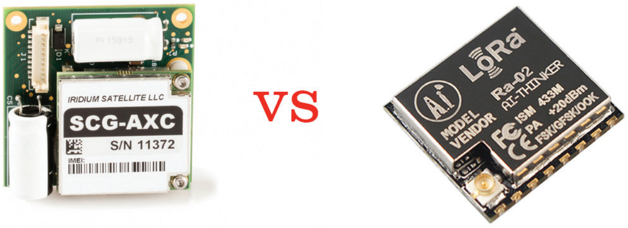


**Figure 14.** LoRa module vs. iridium module.

## 7. Near-space return to home micro drone

### 7.1. Drone structure

We present a near-space drone, which is affordable, robust and may weight below the FAA regulations (300 g). The micro-UAV has a unique RTH control algorithm adjust to near-space conditions and on board black box for storing a wide range of sensor measurements (**Figure 15**). The proposed platform has the following properties:

1. Low-cost, lightweight electric UAV which was equipped with: multiple real-time sensors, HD cameras, a Pixhawk flight controller, GNSS receiver and long-range RF communication system for RC & telemetry data.
2. Smart release mechanism with several parameters for autonomous operation.
3. Near-space flight mode for smart decline.

**Figure 15.** Four different models of RTH micro drones. Each of them was tested for autonomous flight launched from a balloon.

The basic requirement of the UAV is the ability of autonomous RTH or any other Geo location. The UAV needs to be lightweight, aerodynamic wing structure for fast and smooth flight and at list extended range of 50 km for RTH. Denote that in most cases flying back home will require flying against the wind (**Figure 16**).

### 7.2. Smart release mechanism

The smart release mechanism is established from two main elements: mechanical mechanism and autonomous smart release software. The mechanical mechanism has two construction sets: Servo or Fuse wire. The servo is operated with PWM signal, and the fuse wire burns from relay. One of the most important things is the way the balloon attached the release mechanism to the UAV without affecting the UAV fly ability and minimal change of the aerodynamic, because of that the release mechanism mounted on the balloon payload. The autonomous smart release software is an algorithm that gets a several sensor parameters and decides if to release the UAV. The algorithm has the next prioritization: balloon burst, RC signal, altitude, battery, and geo fence. The RC signal is the only parameter that comes from the ground, the rest calculated on the MCU (**Figure 17**).

### 7.3. Near-space flight mode

This mode has few parameters for controlling on smart decline. After the UAV release from the balloon, it will open parachute to altitude that set on the algorithm, the next step is to release

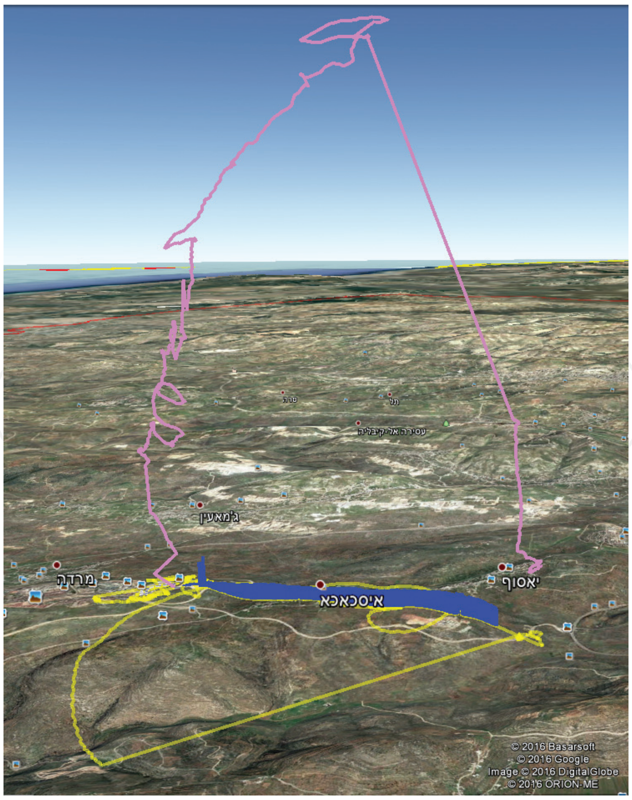


**Figure 16.** Full flight path of an HAB and RTH payload by a micro drone.

**Figure 17.** The RTH payload is going up.

**Figure 18.** Getting back home: A massive UHF transition caused the drone to get into the “fail-safe” state, releasing the drone which in turn flyied back to “home” autonomously.

the parachute and glide with a constant decline rate to altitude that set on the algorithm and then open the motor and fly back home (**Figure 18**).

Currently, we are constructing a micro wing-shape UAV with solar panels for energy harvesting; this will allow us to perform a much longer time and range experiment using super-pressure balloons. Release the drone on a “sunny morning”—allowing it to fly for up to 6 h during daytime covering 100–200 km. Such distance should be sufficient for finding a proper landing region (**Figures 19** and **20**).

### 7.4. Regulation and safety

Launching a HAB requires authorization and following local regulations. We present here some of the US Federal Aviation Administration (FAA) regulations. Please note that even though many countries tend to adapt these regulations, local regulations might differ from the following (FAA Part 101 and 14 CFR Part 48):

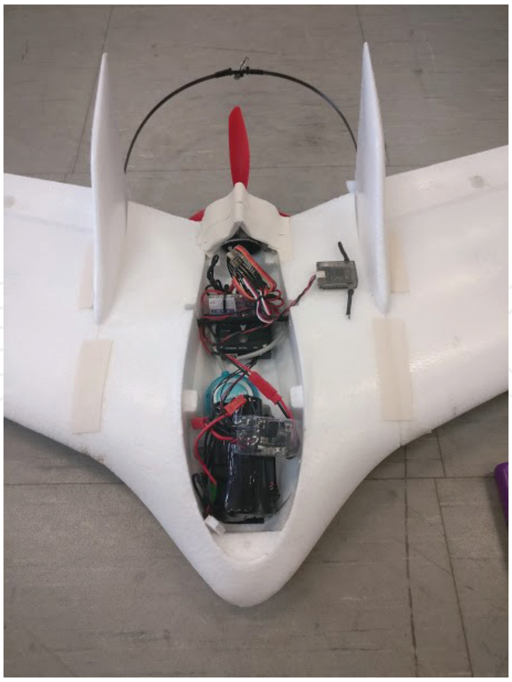


Figure 19. 290 g RTH micro-UAV, with a release carbon strip on its backend.

Figure 20. RTH micro drone lunching.

1. Any cellular phones must be turned off (airplane mode enabled) for any aircraft and/or balloon as soon as it leaves the ground.
2. Any individual payload must weight less than 4 pounds and have a weight-to-size ratio of less than 3.0 ounces/square inch (total weight of the payload only divided by its smallest face).
3. Total payload of two or more packages carried by one balloon must be less than 12 pounds total.

4. The balloon cannot use a rope or other device for suspension of the payload that requires an impact force of more than 50 pounds to separate the suspended payload from the balloon.
5. No person may operate any balloon in a manner that creates a hazard to other persons, or their property.
6. No person operating any balloon may allow an object to be dropped therefrom, if such action creates a hazard to other persons or their property.
7. The owner must register their HAB as part of the FAA's new Unmanned Aircraft System (UAS) laws. The registration number must be marked on each HAB flight.

Here are the main rules of thumb we have used in our HAB launches (on top of the local aviation regulations):

1. It is highly recommended to update the related FAA authorities and get a permission in advance.
2. Validate in real-time the conformation for the launch, a few minutes prior to the lunch.
3. Make sure you are not launching the HAB nearby airports or other no-flight-zones.
4. The overall weight of all payloads should not be more than 1 kg, "Return to Launch" UAVs should weigh less than 500 g—preferable below 300 g (FAA regulations).
5. The maximal declining speed of the falling payload (below 5000 m) should not exceed some velocity (say e.g., 12 m/s).
6. The usage of a parachute cannot guarantee declining speed or velocity. As in this method the overall max weight per square cm should be below some value, we strongly recommend a weight-to-size ratio of no more than 2.5 g per cm square, e.g., a cube payload of 1 l should not weight more than 250 g.
7. Secure each payload's component to prevent its fall.
8. If there are still some safety issues with the HAB, make sure its planned route is not above populated areas—preferably above the sea. Aborting a HAB-UAV mission into the sea is a safe backup plan—and in HAB lots can go wrong.
9. Only launch at a safe zone—where there are no power-lines or buildings.

## 8. Discussion and conclusion

In the last decade, HAB experiments, which were considered esoteric and rare, have become more applicable for scientific researchers and near-space experiments. Today, the overall cost of an HAB experiment can reach up to $500. Radiosondes are commonly used for transmitting the sensory data in real-time. However, using this technology has a limited communication capability and is very hard to customize. New long-range wireless communication technologies such as LoRa allow us to transmit a wide range of sensory data with both substantial low-cost and light weight setup. The maximum data rate provided by LoRa technology is 37.5 kbps, which is sufficient for two-way telemetry along with a wide range of sensory data but is not suitable for high-data-rate applications such as real-time video data. For that we found long-range Wi-Fi techniques to be a prominent strategy: allowing us transmission of live video data up to ranges of about 15–30 km. For long duration application in which the balloon may circle the world, we also present a global two-way communication solution based on Iridium modem.

As the state-of-the-art of communications is still limited, we presented a whole different approach which focused on retrieving the payload in a safe and secure way. Such solution overcomes the need for transmitting the measured data wirelessly—as all the needed information are stored on board of the UAV.

Moreover, this approach highly reduces the risk of losing precious equipment and enables reusing the experiment platform over and over again. In the past, developing and operating an autonomous UAV system was a complicated and costly project. However, in recent years the successful efforts of the toy and hobbies industries to make UAVs accessible and simple to operate provided the opportunity for using UAVs as a common research tool. As such it can be used as a practical and cost-effective solution for returning the payload home with a relatively simple release mechanism and auto-pilot controller.

Based on six different experiments performed during 2016–2017, we conclude that the suggested strategy of using an autonomous UAV as a generic multi-parametric near-space platform is suitable for tropospheric remote sensing and for testing electronic components in near-space conditions.

Current research focuses on exceeding the operational capabilities of long-range Wi-Fi to a full-duplex communication channel and extending its range even further with the development of a high-gain antenna tracker. The deployment of LoRa WAN infrastructure can extend the HAB's communication service over huge areas.

Finally, the current range of RTF autonomous micro UAV is about 30 km. We expect that after optimizing the algorithm for the decline mode (from near space to ground), such range may be extended to 50–100 km with a relatively high probability of success.

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