Low Cost, High Endurance, Altitude-Controlled Latex Balloon for Near-Space Research (ValBal)

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1. INTRODUCTION

Abstract—High-altitude balloons in near space offer the possibility of affordable scientific experimentation and hardware testing for outer space missions. In this paper we present a novel, low cost high-altitude balloon system that achieves multi-day flight using inexpensive latex balloons by automatically venting lifting gas and dispensing ballast to maintain altitude.

Traditionally, superpressure balloons have been used for highaltitude scientific missions; however, despite their long endurance and payload capacity in the tens of kilograms, their cost is in excess of tens of thousands of dollars. Latex balloons are significantly less expensive, typically costing little more than a hundred dollars, but in normal use fly for only a couple hours, rising until reduced atmospheric pressure causes the balloon to stretch beyond its limits. Precision-weighted latex balloons have demonstrated multi-day flights, but such systems cannot change altitude while aloft and offer minimal payload capacity (measuring in tens of grams).

Our system, known as ValBal, offers altitude control capabilities exceeding those of a superpressure balloon at a two order of magnitude reduction in cost. ValBal can stabilize anywhere in its operational range of 10-25 km altitude, and can execute scheduled or remotely commanded altitude transitions during flight. In its current iteration, ValBal can be configured to accommodate payloads on the order of 10000 cubic centimeters and 2 kilograms. In June 2016, a ValBal demonstration mission flew for over 70 hours continuously, surpassing the previous world record of 57 hours, for the longest duration of a latex balloon flight. ValBal has flown twice more since then, including a flight of almost 80 hours. Planned developments will seek to improve the endurance to a week and increase the payload interface capabilities for scientific missions.

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High-altitude balloons are a class of unmanned aerial vehicles whose lack of powered lift introduces both significant engineering challenges and considerable operational benefits. Balloons, which achieve lift through gas buoyancy rather than propulsion, accordingly have less control over their flight path. However, the use of lifting gas significantly reduces the energy needs of balloon systems with respect to propulsive UAVs and allows them to spend significantly longer times continuously aloft than most fixed wing or multirotor vehicles.

Altitude control is the principal form of trajectory control available to high-altitude balloons, as changing mean vehicle density - through the intake and compression of air ballast, the release of pre-loaded ballast, or the release of lifting gas is a low-energy means of affecting balloon buoyancy. Beyond simply changing the balloon's ascent rate, altitude control allows for limited steering of the balloon by exploiting different prevailing winds in different layers of the upper atmosphere. For example, balloons launched at middle latitudes in the northern hemisphere (like much of the United States) that fly at altitudes below 15km will travel predominantly eastward, but can travel west by entering a higher band of oppositeprevailing winds.

Most scientific HAB missions currently rely on one of three types of balloons – latex, zero-pressure, or superpressure. Latex balloons are composed of a highly stretchable polymer and will expand as they ascend, maintaining a very small (approximately 150Pa) pressure difference between the internal lifting gas and surrounding air (overpressure). These balloons can expand by over 100 times in volume, allowing them to reach altitudes in excess of 30km before the latex ruptures. However, due the the low overpressure, the buoyant lift of a latex balloon remains roughly constant with altitude until the ambient pressure decreases to the same order as the overpressure. In practice, the vast majority of balloons will rupture before they can reach neutral buoyancy, limiting the typical time aloft to 3 hours.

Zero-pressure balloons are fixed-volume systems that allow gas to escape through an opening at the bottom of the balloon. Buoyant equilibration will occur at the altitude where the volume of the balloon multiplied by the density difference between the lifting gas and surrounding air is equal to the mass of the vehicle. Due to diurnal temperature fluctuations and corresponding changes in lifting gas density, zeropressure balloons will irreversibly lose gas and buoyancy over time, requiring pre-loaded ballast to be dropped to maintain altitude.

Superpressure balloons are fixed-volume, fixed-mass systems that rely on a high-strength plastic envelope to halt the expansion of lifting gas once the envelope is fully occupied, fixing the density, and thus allowing for buoyant equilibration. Such systems benefit from extremely long endurance (on the order of 100 days) and have the ability to trim altitude by pumping ambient air into an internal volume. However, they are limited by the high cost of producing a balloon envelope capable of withstanding the necessary overpressure.

In this paper, we present an altitude control system for latex balloons that dramatically increases their capabilities for near-space research and surpasses other technologies at capability for altitude control. By venting lifting gas and dispensing ballast while keeping the conventional latex envelope, we are able to increase endurance to multiple days (rivaling that of commercial zero-pressure balloons [5]) while offering dynamic altitude control over an unprecedentedly broad range. Due to the low cost of latex balloons and necessary support hardware, a carefully designed kit could be created for under \$1000 and assembled by non-specialists to fly scientific or commercial payloads. We believe that this technology can significantly lower the barrier of entry to advanced high-altitude research previously inhibited by cost and the lack of adequate altitude-control of existing systems.

The contribution of this paper is threefold: First, we present a novel design for an altitude-controlled latex balloon. Second, we describe the implementation of such design with purposebuilt hardware. Finally, we present results from flight tests throughout North America demonstrating the efficacy of our design.

2. BACKGROUND MATERIAL

Balloon physics

A basic understanding of high-altitude balloon dynamics can be obtained from a simple application of the ideal gas law

$$PV = CMT$$

for a gas with total mass M and given some densitydependent constant C. By conservation of mass, the density ρ follows

$$\rho = \rho_0 (V_0/V)$$

where ρ_0 is the initial density, and V_0 the initial volume. At constant temperature, the ideal gas law gives

$$\rho = \rho_0 (P/P_0)$$

The buoyant lift of a balloon is a function of the density difference between it and the surrounding air, multiplied by the volume displaced by the lifting gas. In terms of the ambient pressure P^A , the lifting gas pressure P^L and the overpressure $P^O = P^L - P^A$, we can express the lift as

$$F = g \frac{V^L}{P_0} (P^A \rho_0^A - P^L \rho_0^L) =$$

= $g V_0^L \left((\rho_0^A - \rho_0^L) - \frac{P^O}{P^L} \rho_0^A \right)$

where we have approximated, for simplicity, that $P_0^L = P_0^A = P_0$. Note, crucially, that the first term in the previous equation is constant while the buoyant lift-limiting term scales as P^O/P^L which, for a typical latex balloon with 150 Pa overpressure only becomes significant above 30 km. This nearly negligible buoyant feedback is both a drawback and a significant advantage of our system – while it requires us to actively adjust the lifting gas volume or payload mass to achieve equilibrium, it also allows us to rapidly and dramatically alter our altitude with minimal expenditure of gas or ballast. Unlike any comparable system, we can target and equilibrate at any altitude between ground level and 25 km or higher, spanning over two orders of magnitude in ambient pressure.

Another relevant but, so far, overlooked component of the balloon dynamics is temperature. From the ideal gas equation varying the temperature of lifting gas at constant pressure will, to leading order, alter the lift as

$$F = \frac{T}{T_0}F_0$$
 or $\Delta F = \frac{\Delta T}{T_0}F_0$

As such, a diurnal temperature fluctuation of 30C due to solar radiation can readily create a 10% variation in lift [4] which must be compensated for by venting gas or releasing ballast. Since this fluctuation occurs at a fixed period of 1 day and has magnitude proportional to the total lift and, therefore, mass of the vehicle, we can readily establish an upper bound on the number of days aloft as

$$N \le \frac{\log\left(1 + \frac{M_{ballast}}{M_{vehicle}}\right)}{\log\left(1 + \frac{\Delta T}{T}\right)}$$

For a 1-to-1 ballast-to-vehicle mass ratio and 10% variation in temperature, this bound sets a limit of 7 days – a figure reasonably consistent with the data obtained from test flights.

Existing work

Existing efforts to develop passively altitude-controlled latex balloons have centered on the buoyancy limiting properties of latex balloon overpressure (as discussed in the preceding section). Passive altitude-stabilizing latex balloons must be filled with a precisely calculated mass of lifting gas based on the weight of the vehicle being flown. Such balloons equilibrate and maintain their altitude without active controls, but are capable of operating solely in the upper stratosphere and cannot carry payloads in excess of tens of grams. While such systems have demonstrated extended duration latex balloon flight [1], they are not suitable for carrying most scientific payloads and cannot deliberately change their altitude while aloft. The system described in this paper suffers from neither of these limitations and delivers endurance beyond the highest achieved using previous latex balloon techniques, despite relying on lower quality and more easily sourced latex balloons.

3. TEST PROCEDURES

The balloon system, known as ValBal (a contraction of Valve and Ballast, the two altitude control mechanisms) has been extensively simulated and completed 11 flight tests ranging in duration from 10 minutes to almost 80 hours. Seven revisions of the vehicle were built and flown between January 2015 and December 2016, with the longest to date occurring in



Figure 1. Flight profile of various ValBal missions compared to standard latex balloon flight.

November 2016 when Vehicle 6.1 (ValBal Flight 10) flew across the continental United States in 79 hours, 6 minutes. ValBal Flight 10 re-set the world record for the longest continuous time spent aloft by a latex balloon, traveling over 3,500 miles from Modesto, California to outside of Quebec City.

Test flights are carried out to validate design decisions, learn more about the operating conditions in the relevant portion of the atmosphere, and demonstrate system performance. All vehicles report telemetry and accept commands over the Iridium network while in flight, allowing operators to monitor the vehicle's status and change altitude control constants or terminate the flight remotely. Telemetry downlink and command uplink occurs on a configurable interval typically in excess of 5 minutes, meaning that flights are largely autonomous. Test flights are conducted primarily in US airspace, with balloon vehicles launched from Laird Park in Modesto, California. In the interest of proving ValBal's ability to traverse large longitudinal distances - building to an ultimate demonstration of the ability to circumnavigate the Earth - launching during winter months is preferred to maximize eastward winds. Although winter launches tend to have higher eastward wind speeds due to seasonal variation in the Northern Hemisphere, test flights are conducted yearround.

The dynamic nature of the lower stratosphere makes experimental consistency difficult to achieve between flights. Certain conditions, such as the low temperatures at altitude (daytime temperatures of -60C are common), are consistent across flights, and thus allow for the testing of system robustness. However, other flight variables - in particular, weather phenomena - are difficult to predict, and test vehicles are intermittently subjected to extreme conditions. For example, on ValBal Flight 5, Vehicle 3 passed through a severe thunderstorm - which it successfully navigated with less than 10% variation in altitude from its programmed setpoint, but at the cost of significant ballast mass.

Because test flights occur primarily over land, vehicles are often recoverable, even when they land significant distances from the launch site. Seven of the eleven launches to date have ended in the successful recovery of the vehicle, with the furthest recovery that of a vehicle which landed 40 miles east of Quebec City. Recovered vehicles are a valuable source of flight data, as their onboard flight logs contain significantly more information than can be reported through in-flight telemetry. Recovered vehicles are also re-launchable with minimal maintenance. Five of the eleven launches to date were relaunches of a recovered ValBal system, and as of this writing the most recently launched system - the aforementioned vehicle recovered from Quebec City - has already been relaunched once and is awaiting an opportunity to be relaunched a second time.

4. DESIGN AND SETUP

Overview

The ValBal vehicle is purpose-built to meet the unique requirements of extended duration latex balloon flight. The following sections will describe the development efforts and most recent iterations of the vehicle's structure and mechanisms, avionics, flight software, and altitude control algorithms.

Mechanics

As with most aerial vehicles, our system is designed to perform reliably in its environment while minimizing mass to free up capacity for more payload, ballast, or power, thus maximizing our capabilities. With this in mind, the vehicle was constructed primarily out of acrylic and polycarbonate plastics, with carbon fiber rods carrying the load from the ballast hopper to the neck of the balloon. Our latest vehicle had an empty (ballast-free) mass of 3kg, which can be broken down as follows: balloon (1.5kg), batteries (550g), structural mass (300g), insulation (250g), avionics (200g), and parachute (200g). Our balloons (typically Kaymont 1500g) are capable of sustaining a total lift of up to 9kg, leaving 5kg free for ballast and payload.

Aside from the obvious mass constraints, our vehicle must handle a rather harsh environment; most notably, the 100C temperature swing between ground level and the -60C temperatures frequently observed at altitude. In addition, humidity at lower altitudes can lead to icing, potentially blocking



Figure 2. Picture of the vehicle that flew on Flight 9.

our electromechanical systems. Some components, such as our batteries, cannot function in extreme cold, so insulation and heating are necessary to keep them functional. Judicious consideration of which components require heating has enabled us to significantly reduce the power requirements of our vehicle by shrinking and isolating the thermal enclosure, and removing extraneous wiring and all mechanical linkages from the boundary between the heated compartment and surrounding air. This approach requires all electromechanical systems to operate in cold for the full duration of the flight.

Valve design— To prevent issues with icing while sealing tightly when closed, the valve seal consists of a flat latex sheet pressed against the opening of a PTFE tube. The valve arm is driven by a low-current gearbox that is optimised for cold by applying low-temperature compatible Dow Corning Molykote 33 grease to all moving parts. Since the valve may fly for over 10h at a time without needing to be used, a worm-drive gearbox was selected to allow the motor to be depowered without risking back-driving of the gearbox. A low-profile compression spring underneath the flat seal allows it to pivot slightly around the horizontal axis to align to the opening, and also exerts some pressure along the vertical to ensure that the valve remains sealed when the gearbox is inactive. Position feedback is achieved through a potentiometer coupled to the axle of the valve arm.

Flight termination and controlled descent—To reduce overall electromechanical complexity, the valve arm is also used for flight termination. When rotated substantially beyond the

nominal 'open' position, the arm engages a spring-loaded latch which releases one of the three corners of the neck adapter. The remaining corners readily disengage as the neck adapter pivots away from the upper plate, separating the payload from the balloon and also leaving the neck of the balloon open, ensuring that it, too, will land promptly. The entire valve assembly is able to slide vertically along the loadbearing carbon fiber rods that support the avionics enclosure and ballast. Springs along two of the four rods ensure that once the valve assembly is no longer supporting the mass of the vehicle - either due to intentional termination or balloon rupture – the assembly will move downwards, immediately releasing the parachute. Prior to termination, the parachute is held up by its midpoint to prevent tangling and ensure that it cannot catch and accumulate ballast that is dropped from the dispenser.

Ballast design-To avoid the complexities inherent to irregularly granular or liquid ballast, a uniformly granular material, in the form of biodegradable 6mm BB pellets, was selected. The pellets are manufactured to a high degree of sphericity and with good quality control, thus allowing for a very high degree of consistency during operation. A DC gearmotor treated with Molykote 33 is used to drive a dispenser wheel which drops individual pellets at a rate of up to 4 per second, corresponding to a ballast drop rate of 1g/s. The entire ballast container can, thus, be emptied in 1.5h, though typical drops will occur in increments of 20s distributed across a few days of flight. Since the ballast motor must run for the duration of the ballast dropping procedure, it is optimized for reliable cold-start (typically starting at 1V but driven at 5V) and low current (30mA). In the event that a pellet does jam the dispenser wheel, it is designed to stall safely and reverse every 20s to free the jammed pellet. In ground testing, the system would seize roughly once per 2000 pellets, and never irreversibly. We have now dropped over 40000 pellets at altitude and never experienced any issues with the dispenser, to the point that we decided to forgo a jam-detecting encoder in recent vehicles to reduce complexity. Lastly, the low terminal velocity and biodegradable nature of the pellets we use ensures that they pose no threat to persons or property on the ground, and the low price makes ballast costs lower than the per-mission cost of gas or satellite communications.

Thermal considerations—Ambient temperatures below -60C make the lower stratosphere a challenging thermal environment, in particular for electronics. The vehicle thus contains an avionics compartment insulated with layers of expanded polystyrene foam and fiberglass-aerogel, with a cumulative thermal resistance in excess of 1W/100K. To prevent conducted thermal losses, all of the wires passing out of the compartment have been reduced to a single flat flexible ribbon cable, the small cross-section of which allows for low conductive heat flow and minimal pass-throughs in the insulation.

Heat is produced inside the compartment by the power dissipation of the avionics, as well as a resistive heater which is enabled at night to help the compartment remain above freezing. With the exception of power transmitted during satellite telemetry downlink and used to drive motors, all power consumed onboard the vehicle is converted into heat and helps the avionics remain warm. The standby power dissipation of the avionics is sufficient to keep the avionics compartment at 20 - 30C (a 70 - 80C differential with respect to ambient) during the daytime.

Though simulation indicates that the compartment's optimal temperature for power conservation is -17C, the 0C nighttime



Figure 3. ValBal MkVI mechanical design: (a) outlined for the full vehicle. (b) detail of the valve mechanism showing the valve in a partially open position. An exploded view of the ballast system (c) shows the 8-pellet-per-revolution dispensing wheel. Flight termination is accomplished through driving the valve from its closed position (d) to an over-open position (e) at which the neck release latch is triggered. Loss of lift at the neck automatically triggers the spring-loaded parachute release system shown on the right of (d) and (e).



Figure 4. Plot of temperature versus time for Flight 8. Notice the temperature being held at 0 degrees Celsius during nighttime by heaters, and a local noon dip due to occlusion of the avionics compartment by the balloon.

setpoint was chosen based on the derating of component operating temperatures. Though this draws more system power than allowing the vehicle to run colder, margins on stored energy for target mission durations are sufficient to allow this warmer minimum temperature.

Electronics hardware architecture

The avionics system is controlled by a single Teensy module, an open ARM Cortex M4 development board capable of supporting the popular open source Arduino framework. As the vehicle's single onboard processor, the Teensy is used for all status monitoring and control. It polls an array of temperature and barometric pressure sensors over an SPI interface, supervises battery voltage and current, communicates with the Iridium modem and an onboard GPS receiver over UART, controls the valve and ballast actuators, and enables onboard heaters.

Reliable altitude determination is critical to altitude control. ValBal carries an array of four barometric pressure sensors capable of reporting pressure at 25 Hz, based on internal oversampling at rates of about 400 Hz. These pressure readings are averaged and IIR filtered within each sensor, and converted to altitude measurements onboard the Teensy based on the US1976 standard atmosphere model.

The operating temperature range of the avionics is one of the principal drivers of the requirement that the interior of the insulated compartment remain above 0C. In addition to components not rated for operation at lower temperatures, such as the supercapacitor on the Iridium modem, battery capacity is



Figure 5. Vehicle avionics block diagram.



Figure 6. Assembled ValBal avionics.

significantly impacted by temperature, decreasing markedly at temperatures below freezing. Internal temperature measurements are thus used to trigger a resistive heater when incident solar radiation and the vehicle's standard operating power are not sufficient to keep the avionics above freezing.

Vehicle power is provided by an array of nonrechargeable lithium thionyl chloride ($LiSOCl_2$) cells. These cells offer very high specific energy (500Wh/kg), almost 100% better than the specific energy of consumer-grade lithium ion cells. This high energy density comes at the cost of very low specific power. Each 17 g primary cell can supply no more than 10 mA before suffering severe capacity degradation. Cell voltage varies based on load and state of charge but remains relatively constant for the first 70% of cell life, and is approximately 3.5 V at flight loads. The flight battery pack consists of 32 cells in parallel, for a maximum total installed capacity of approximately 250 Wh. Individual cells are replaceable and removable, meaning that pack capacity can be selectively reduced to save cost and vehicle weight. The limited power output capability of the vehicle battery means that high-current devices cannot be run for extended periods of time. To accommodate this requirement, the valve and ballast motors were selected for low (<100 mA) running current, and the high current draw of the Iridium modem and supplementary heater are modulated. The Iridium modem, which transmits and receives one telemetry and control packet over a configurable interval (typically five minutes), is driven by a supercapacitor which requires several seconds of high-current charging every transmission period. However, this is brief enough to prevent significant impact on battery capacity. The PCB trace heater integrated into the battery pack consumes on the order of 400 mA when active; though the need to heat the payload at night has a negative impact on battery life, this is somewhat mitigated through the use of pulse width modulation to reduce the average current consumption.

Flight software and altitude control algorithm

The altitude controller is responsible for deciding between the two actions that the system can perform: vent gas or drop ballast. In general, the guiding philosophy is to limit both actions as much as possible: endurance demands a conservative use of the ballast and gas budget. Hence the goal is not necessarily to keep a specific altitude (which would be very ballast consuming given the fluctuating air currents), but to keep the balloon within a buffer zone: the larger it is, the better the endurance. Especially important is the ability to react quickly to sunrise and sunset: changes in temperature of the gas translate to a change in net lift, and the system ought to react accordingly. With that in mind, the controller keeps track of two variables: the venting incentive, and the ballast incentive. When either of those goes above a threshold, the corresponding action is performed.

Three system variables contribute to those incentives: the ascent rate (since the goal is to remain at a somewhat constant altitude, large ascent rates should trigger some action), the distance to the desired altitude setpoint, and the distance since the last action performed (to avoid repeating the same action before feedback takes place). Venting and ballast incentives are the result of weighting those three parameters in the following fashion:

$$I_{vent} = c_1 h + c_2 (h - h_T) + c_3 (h - h_{lv})$$

$$I_{ballast} = -c_4 \dot{h} - c_5 (h - h_T) - c_6 (h - h_{lb})$$

Here h is the altitude, h is the ascent rate, h_T is the altitude setpoint, and h_{lv} and h_{lb} are the altitudes where the last venting and ballast action took place, respectively. The values of the constants $c_{1,...,6}$ were determined by running simulations of the balloon and validated during flight: the most recently used values were $c_1 = c_4 = 1 \text{ s/m}, c_2 = c_5 =$ $1/1000 \text{ m}^{-1}$ and $c_3 = c_6 = 1/1500 \text{ m}^{-1}$. If either of the incentives exceeds 1, the corresponding action is triggered by the microcontroller.

We can look at the response of each individual term to see how the system reacts: in the absence of other variables, venting is triggered when the ascent rate goes above 1 m/s and ballast is triggered when the ascent rate is more than -1 m/s. The altitude difference term governs the rough buffer zone: c_2^{-1} meters above the setpoint and c_5^{-1} meters below the setpoint. The third term similarly would trigger a venting action when the balloon is more than c_6^{-1} meters above the altitude where the vehicle last vented. Ultimately, actions are determined by the sum of these components. This solution is simple to implement but requires good knowledge of both altitude and ascent rate: if the readings are too noisy, actions can be incorrectly triggered. This is further complicated by the fact that the measurement noise is determined by pressure (since altitude data comes from barometers): however, at flight altitude, the same change in pressure corresponds to a much bigger change in altitude, and the uncertainty grows accordingly. At 15 km, RMS white noise on altitude is about 5.6 times bigger than at sea level. To reduce measurement uncertainty, and provide redundancy in case of sensor failure, the vehicle is equipped with four pressure sensors. Sensor failures are identified by looking at large deviations in the absolute pressure consensus of the different sensors or sudden changes in pressure that cannot be explained by the balloon's movement. Inconsistent readings are automatically disregarded by the altitude controller and reported in vehicle telemetry. Sensors can also be enabled and disabled remotely by means of satellite communications if telemetry reveals a pattern of failure. For each functional barometer, the ascent rate is computed by low-pass filtering the readings over the span of about 15 seconds. The final ascent rate is finally computed by taking the average of the individually reported ascent rates.

Other duties of the flight software include communication to and from the balloon. An Iridium modem is used for that purpose, allowing short data bursts every few minutes. To work within the bandwidth limitations of the channel, 47 system variables are compressed into 50 bytes, with the possibility to report 43 additional variables in 50 more bytes for debugging purposes. Telemetry includes data on the vehicle's ascent rate, altitude, location, power (temperature, total energy expended, battery voltage, and minimum, average, and maximum current of each of the subsystems), controller, and sensors (including maximum and minimum values, and RMS noise). In order to gather more data and gain insight into the controller's response, the altitude and velocity changes in between transmissions are sent interpolated. More importantly, the Iridium modem offers up-link capabilities: flight controllers on the ground are able to send up to 60 different commands to the vehicle, including changing the controller constants and communication interval. In case of any malfunction, specific sensors and power subsystems can be disabled and enabled from the ground, and manual venting and ballast events can be triggered.

Besides the possibility of manual intervention, the flight software includes autonomous power protection mechanisms. If overcurrents are detected, individual subsystems that draw considerable amounts of power (like the valve and ballast motors, the communications module, and the GPS) can be disabled by means of a field-effect transistor. In case of an inflight restart of the microprocessor, the system is able to enter in a safe boot mode in which only functional subsystems are progressively enabled, allowing for a successful continuation of the mission.

5. FLIGHT PERFORMANCE

The eleven ValBal flights conducted to date have successively advanced towards the goal of low-cost, high-endurance flights for research payloads. Five initial flights in 2015 proved the feasibility of the concept, with the final and most successful achieving an endurance of over 23 hours. 2016 brought six more flights, the third of which broke the previous world record for latex balloon endurance 57 hours, 2 minutes with a flight time of 70 hours, 10 minutes. A later ValBal flight



Figure 7. Duration of the last nine ValBal missions. Flight 11 was terminated early to permit recovery.

broke this record again, with a flight time of 79 hours, 6 minutes.

The first record-breaking flight, ValBal Flight 8, is a very compelling case for the system's capabilities and potential. After a few manual corrections in the first few hours, it flew a majority of its flight completely autonomously. Despite an early loss of venting ability after an electrical malfunction in the valve, the mission continued successfully with a looser upper altitude bound while still using ballast to compensate for losses in lift. The mission ended almost three days after launching, with about 40% of its ballast left. Assuming a 10% diurnal temperature fluctuation, the ideal endurance for the quantity of ballast expended is 3.7 days, meaning that flying with loose altitude bounds brought us very close to saturating the theoretical endurance limit. In addition, this flight shows the potential to carry multi-kilogram research payloads for multiple days. The likely cause for its end of mission is a combination of mechanical stress of the balloon (partly due to reduced altitude control) and UV radiation degrading the latex. However, it should be noted that this launch took place close to summer solstice and was under strong solar radiation for a majority of its flight, and hence missions flown during the winter would suffer less from radiation effects.

ValBal Flight 9, launched about a month later, landed in New Mexico almost 48 hours after liftoff. Unlike the previous flight, its endurance was limited by ballast: a leaky valve, resulting from errors in calibration and noise in the potentiometer, led to a subtle loss in lift that had to be compensated for by dropping ballast. However, the temporary losses of lift served as a very powerful demonstration of our ability to adjust altitude. After equilibrating at an altitude of 12km, the vehicle occasionally transitioned to a higher or lower altitude accumulating over 45km of additional altitude change over two days before running out of ballast and descending. An improved control algorithm would eliminate the unwanted fluctuations, leaving enough reserve ballast to accommodate tens of kilometers of intentional altitude change over the course of a scientific mission. This maneuverability could be applied to track specific atmospheric layers that are of interest to a scientific payload as a function of time, or to select layers of distinct wind velocity in order to reach a certain geographic location, atmospheric region, or guide the payload to a suitable site for landing and subsequent recovery. While the capability to adjust altitude slightly is present in other, typically much more expensive, balloon systems, our vehicle traversed a range of altitudes from 10km to 20km, corresponding to a 5-fold variation in ambient pressure and balloon volume, and did so rapidly and repeatedly, beyond the capability of fixed-volume balloon systems. In addition, the flight emphasized the efficacy of our bidirectional communications system which allowed us to rapidly react to malfunctions and implement changes to on-board control algorithms to stabilize the vehicle. The power consumption figures - received by means of satellite communications and after recovery of the landed vehicle - showed that it had power for almost two weeks of flight despite the challenges presented by the cold external temperatures. Its flight profile shows the ability of ValBal to fly at many different altitudes in a single flight, as well as the adaptability of the platform to malfunctions.

ValBal flight 10 again demonstrated the platforms capabilities, flying for 79 hours and 6 minutes, landing near Quebec City, and re-breaking the endurance record. The balloon envelope was recovered alongside the payload, providing data on how the material degrades at altitude. The most recent flight, ValBal flight 11, was purposefully cut-down prior to reaching the Atlantic Ocean to permit recovery. The data from these two flights will allow us to further refine our flight control algorithm, thus conserving ballast and increasing flight capability. Together, the most recent four flights demonstrate that ValBal can consistently fly far longer than conventional latex balloons and far cheaper than other highendurance alternatives.

Ultimately, previous flights show that endurance is limited by three main factors: ballast capacity, energy capacity, and chemical degradation of the balloon. Cold-running mechanics and high quality insulation have reduced required operating power to the point where energy is not a limiting factor. The two open challenges are UV degradation of latex and the ballast budget. The former, which only became an issue after almost 3 days during summer solstice, will require research into chemical treatment of the balloon's to protect it against solar radiation. The latter becomes a problem in very long missions or missions carrying a heavy payload, and current research aims to improve the control algorithm to conserve as much of the ballast budget as possible.

6. CONCLUSIONS AND FUTURE WORK

A heritage of successful flights has demonstrated that the technology described here is both physically possible and realizable in the absence of significant resources and expertise. We have shown that active control of payload mass and lifting gas volume, the duration of these latex balloon flights can be extended from the typical three hours to multiple days. Furthermore, the variable volume of latex balloons enables our system to rapidly and repeatedly adjust altitude over a range that is inaccessible to most fixed-volume balloons. We demonstrate the ability to fly in a ballast-efficient mode that comes close to saturating the predicted minimum bound on ballast expenditure, and also show the ability of the system to make altitude transitions on the order of 10km mid-flight.

Further work - through improvement of the balloon envelope's UV resistance, optimisation of control algorithms, and reduction of vehicle mass to accommodate more ballast seeks to extend the endurance of a ValBal flight to a week or more. Extending the in-air mission duration increases the platform's utility to atmospheric research, and opens up the possibility of flying missions that circumnavigate the Earth. In parallel, we are working to dramatically simplify the construction process for ValBal vehicles with the ultimate goal of creating a kit of readily outsourceable modules that could be put together by a non-specialist in under 5 hours. The success of the ValBal program to date has attracted the interest of researchers with diverse fields of study such as the effects of near-space conditions on biological samples, foliage density modeling, and radio glaciology. One proposed mission candidate deserving of special mention is aerial radar sampling of ice sheets. Potential collaborators have proposed surveying the Greenland ice sheet through several flights over the course of a summer season to understand the distribution of subsurface meltwater within the sheet and the structural effects of the melting period. Similar radar systems could be flown over the Antarctic ice sheet, where strong polar vortices and the extended endurance of the ValBal system would allow for one or more circulations over the entire sheet. ValBal's low cost and easy assembly makes it particularly well suited to flying missions in remote areas such as ice sheets, as the equipment and personnel required to launch are far lower than other airborne platforms.

The demonstrated success and considerable potential of the ValBal platform make it a noteworthy and compelling entry into the scientific mission-carrying unmanned aerial vehicle space. Development efforts to date have yielded a high performance platform, and future efforts will concentrate on increasing the vehicle's suitability for scientific missions and ease of assembly and launch.

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