AIAA Balloon Systems Conference
4 - 7 May 2009, Seattle, Washington

AIAA 2009-2810

Advances in Controlled Meteorological (CMET) Balloon Systems

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Over the past five years, small altitude-controlled balloons have been developed for atmospheric research and deployed in several major field campaigns. These Controlled Meteorological (CMET) balloons have been operated at altitudes from sea level to 18,000 feet, at latitudes from 18 to 80 degrees north, and for periods of up to five days. CMET balloons are now sufficiently simple to prepare and launch that they are being mailed to scientific collaborators oversees and operated remotely via satellite, greatly reducing the cost of making in situ atmospheric measurements. The balloon payload has been redesigned around a novel eight-parallel-processor microcontroller that enables exceptional flexibility and control with appreciable reductions in power consumption and weight. Miniature chemical sensors (carbon dioxide and sulfur dioxide) are now being used for quantifying contaminants and locating atmospheric layers. These new capabilities are being combined with near-real-time data processing, visualization, and control to enable CMET balloons to follow contaminant plumes in three-dimensional space, make repeated profile observations of mixing and dispersion, and report up-to-the minute position information to aviation safety officials. Successes and failures during recent campaigns in Mexico City, Hawaii, and the Arctic are discussed. Advances in balloon design and operations are described in the context of past flights and potential future applications.

I. Introduction and Background

For more than a century, meteorological balloons have provided accurate in-situ profile measurements of atmospheric properties and, more recently, trace gas species. This paper describes recent advances in the development of a Controlled Meteorological (CMET) balloon that can remain aloft for days at a time and be commanded to continuously change its altitude during flight[1,2]. These attributes allow the balloon to perform repeated soundings, track polluted layers, and navigate using wind shear.

The standard CMET balloon consists of a zero-pressure main envelope containing approximately 750 liters of helium. Inside the main envelope is a small high-pressure balloon (approximately 100 liters at 25 kPa superpressure) that acts as a lightweight helium reservoir. When the CMET balloon is commanded to ascend, helium is released into the zero-pressure balloon. Descent is accomplished by pumping helium back into the reservoir balloon. A small command and control payload (approximately 350 grams) includes a micrcontroller, various sensors, a gps receiver, satellite modem, pump, valve, photovoltaic panel, and batteries. The small size and controllability of CMET balloons confers a number of advantages. They can be transported in automobiles, launched in windy conditions, and flown safely in areas that are inaccessible by other means.

II. Technical Developments

Recent technical advances in the CMET balloon's payload electronics as well as its flight and ground software have significantly increased its capabilities. These are described below followed by three examples from recent field studies.

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A. Payload Hardware

Over the past two years, the CMET balloon's electronics payload has been redesigned around an unusual new microcontroller with multiple parallel processors. As described below, the board is simpler and more easily reprogrammed than its PIC-based predecessor. This has allowed the implementation of new operating modes for the balloon, data compression, and efficient power management.

The control board oversees communications, data acquisition, and the operation of peripheral devices on the balloon. In the standard configuration, the board reads data from eight sensors and a GPS receiver, controls a pump, valve, fan, terminator, photovoltaic panel, LED strobe, and Iridium satellite modem for two-way communication with the operations center. Four timing cycles run simultaneously to allow for superpressure regulation (0.5 sec), altitude control (10 sec), science data collection (10 seconds to 1 hour), and satellite communication (90 seconds to 4 hours). All major components are shut off between cycles to conserve power. A lithium polymer battery (e.g., 1450 mAh @ 16.8 V) will power the payload indefinitely with the aid of a photovoltaic panel.

The core of the control board is a new micrcontroller that was developed by Parallax Inc.of Rocklin, California. Introduced in 2006, this “Propeller Chip” has eight parallel processors (cogs) that can each run user-generated code independently. A common clock drives all eight processors simultaneously while coordinating access to common resources (e.g., global variables) in sequence so as to avoid conflicts. Programs are written in a high-level object-based programming language (Spin[3]) that invokes assembly language programs for time-critical tasks (e.g., downloaded routines for serial communication). A software-controlled phase-lock loop sets the clock speed between 20 kHz and 80 Mhz, allowing the trade off between performance and energy conservation to be varied in real time during program execution.

These attributes make the Propeller chip ideally suited low-power embedded systems that must operate complex peripherals over a wide range of time scales. On the balloon payload, cog (0) runs the main 10-second control cycle (measurements and altitude control decisions) with an embedded 0.5 second cycle to regulate the superpressure via the pump and valve. Under direction of cog 0, additional cogs handle GPS warmup and control, modem warmup and control, serial communications, high-speed valve control, and the LED strobe. Once a process is initiated on a new cog, it runs to completion without further intervention from cog 0. For example, when data transmission is initiated, the new cog handles the modem initialization and bi-directional communication via satellite. At the end of the process, global command variables (e.g., setpoints, control parameters, etc.) are updated, a success flag is set, and the modem and its associated cog shut down to conserve power.

This straightforward programming environment has enabled some substantial improvements to be implemented while at the same time reducing the need for dedicated engineering support. The payload has since been upgraded to use Iridium's new 9601 satellite modem, reducing the weight, cost, and power consumption of this peripheral device by approximately half in comparison with its predecessor. Transmitted data is sent in binary format, with a 25-fold gain in throughput (and reduction in data service fees) compared with comma delimited ASCII text. Finally, a dedicated auxiliary instrument port has been added to allow additional sensors and mission-specific devices to be easily integrated into the payload.

B. Altitude Control Algorithm

The most substantial improvement has been to the balloon's control algorithm. Earlier balloons used a proportional-derivative routine with manual correction of the integrated altitude error by operators on the ground. This effective PID control generally maintained the desired altitude but power use by the pump was unacceptably high as the algorithm aggressively corrected small altitude errors due to atmospheric turbulence. Furthermore, large vertical velocities (especially downdrafts) could cause overcompensation and loss of control. While relaxing the control parameters (PD gain constants and a dead band) ameliorated these problems, instability and overshooting became increasingly problematic; parameters needed constant adjustment during flight to account for changing conditions and objectives.

The new control algorithm simply maintains the ascent rate (within upper and lower limits) if the balloon is lower than a minimum set altitude. A similar descent rate is maintained of the balloon is above a maximum set altitude. If the ascent or descent rate falls outside of these limits, the valve or pump is activated as needed to achieve a set change in buoyancy. This direct control over the balloon's ascent rate is possible because the pressure altitude can be measured with great precision (+/-10 centimeters) enabling the ascent rate to be calculated during every 10-second control cycle. The main advantages of this limit-based control are that 1) it is simple to understand and modify during flight, 2) absolute limits prevent run-away ascent during launch, 3) the pump and valve are rarely activated during level flight, 4) the ascent rate can be tightly prescribed to achieve near-perfect atmospheric soundings.

C. Data Processing and Visualization

Data is sent to and from the balloon via Iridium's Short Burst Data (SBD) service. Messages arrive at the laboratory as email attachments which are then automatically extracted, concatenated, and processed using Mathworks' MATLAB software[4]. Balloon trajectory maps, Google Earth images (kml files)[5], and vertical profiles of winds and meteorological variables are then distributed in near-real time through a dedicated web site (www.science.smith.edu/flights). Increasingly, complex post-flight analyses (e.g., turbulence, vertical mixing, plume dispersion) are being run during flight and integrated into the data visualization. These data products allow long-distance collaborations where scientists in different parts of the world can examine the same data at the same time and thereby contribute to critical flight decisions.

D. Balloon Envelope Improvements

With their large surface-to-volume ratio and long flight durations, CMET balloons are prone to excessive helium loss. For this reason, a aluminum oxide coated polyethylene terephtalate (PET) film is used for the main envelope. This packaging film has better barrier performance than the aluminized (silver) films commonly used for commercial (e.g., party) balloons. In addition, it is clear and non-conductive to electricity, minimizing solar heating as well as the hazards to power lines.

PET film, however, is extremely difficult to seal. In the packaging industry, it is typically coated with an adhesive; seals can them be made simply by joining the adhesive-coated sides with heat and pressure. The drawback of this method is that a layer of adhesive coats the entire balloon envelope; in our tests, the thinnest adhesive layers that could be produced in a commercial facility approximately doubled the specific weight of the film.

Other sealing methods proved equally problematic. Solvent-based adhesives fail to set between the layers of the high-barrier film while adhesives either fail to adhere to the film (e.g., epoxies), slowly peel apart at folds (e.g., specialty tapes), or lose all their strength in cold temperatures (e.g., most hot-melt adhesives). After extensive testing and many balloon repairs in the field, it was found that the polyurethane hot melt adhesives used in the sail-making industry are well suited to sealing PET film: the hot melt process produces a gas tight seal and initial strength while crosslinking of the polymer (with water molecules from the air) greatly increase adhesion over a period of several days. In laboratory tests using dry ice, seals made in this manner retain significant strength at temperatures down to minus 60-70 degrees Celsius.

III. Recent Field Studies

The technological improvements described above have greatly reduced the cost and complexity of CMET balloon flights. Whereas earlier flights required that a field team of several people at the launch site (sometimes for weeks at a time), the balloons can now be mailed to collaborators overseas, inflated and launched within hours, and operated by a single person. Three recent research campaigns showcase the advances made in CMET balloon design and deployment strategies.

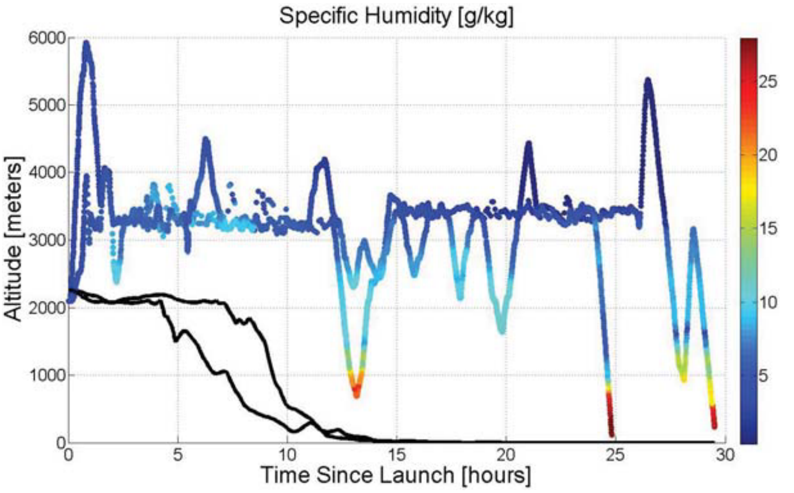

Figure 1. Continuous soundings made by two CMET balloons traveling for 28 hours from Mexico City (at left) to the U.S. border.

A. Mexico City, 2006

During the Megacity Initiative: Local and Global Research Observations (MILAGRO) study, a total of seven CMET balloons were flown with the aim of tracking long-range polluted outflow from Mexico City. Five of the flights were successful and two of these tracked a major outflow event and helped to guide one of the mission aircraft (the NCAR C-130) to the polluted airmass 24 hours downwind of the city. The balloons were prepared at the MILAGRO Aircraft Operations center in Veracruz and transported to launch sites six hours away in Mexico City via minivan. Once airborne, they were commanded to perform repeated soundings in order to profile the evolving thermal structure and wind shear driving dispersion of the polluted outflow (Fig. 1). While these flights achieved their goals, they occurred prior to technical development described in this paper; the work was therefore personnel intensive and challenging; nine people (including four undergraduate students) assisted in preparing, transporting, and operating the balloons.

B. Norway, 2007-2009

Based on the experience in Mexico, a more efficient approach was taken for the International Polar Year (IPY) campaign in the winter of 2007; seven balloons were shipped to collaborators Andreas Stohl, Lars Hole, and Sibyl Brunner at the Norwegian Institute for Air Research (NILU). These balloons were launched from locations in Andøya and Ny-Ålesund while being operated from remotely from my laboratory in the United States (Fig. 2).. Initially, the extreme cold caused the balloon seals to fail, necessitating repairs in the field. During flight, the balloons quickly gained weight (likely due to ice formation) and fell from the air when they remained in humid layers (>90% RH) for more than approximately 20 minutes. Subsequently, a strategy was developed in which balloons performed an initial sounding to identify the humid layers and were then placed at the altitude with the driest air. This strategy has worked reasonably well with one balloon remaining in the air for 14 hours before being brought down by encroaching humidity. In 2008 and 2009, two more Arctic flights were attempted, both having the new payload and software described above. While the these new balloons were far simpler to operate, the first suddenly lost communication five hours into the flight and the second was unable to find suitably dry air and came down due to ice formation. Work towards an extended low-altitude balloon flight in the Arctic is continuing with additional attempts planned for 2009.

Figure 2. CMET balloon launched from Ny-Ålesund Svalbard, Norway. *The balloon was shipped in a small package and operated from the United States. Photo Credit: Lars Hole*

C. Hawaii, 2008

Building on the technical advances spurred by the IPY flights, two CMET balloons were shipped to Hawaii and launched by collaborator Adam Durant into the volcanic plume emanating from the Halema`uma`u creator on Mt. Kilauea. These balloons carried sensors for qualitatively measuring sulfur dioxide (SO2-BF from AlphaSense Inc.) and carbon dioxide (General Electric TelAire 6004). While high surface winds (10 m/sec) and rocky terrain presented the most difficult launch conditions experienced to date, both flights

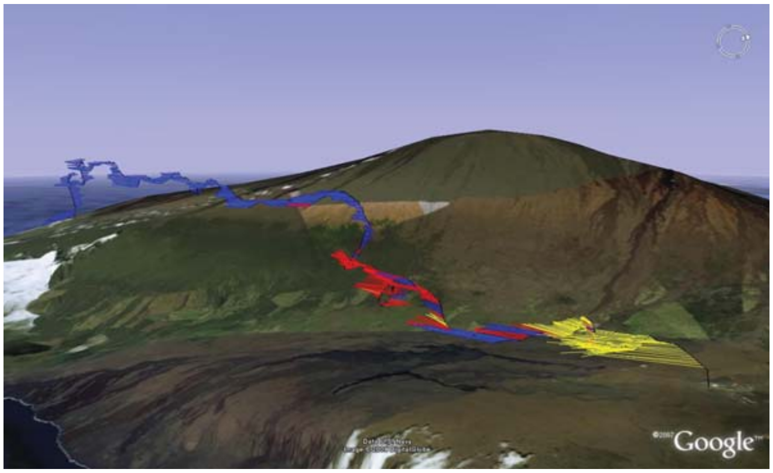

Figure 3. Real-Time Google Earth image of a CMET balloon launched from an active volcano in Hawaii. *The color of the wind barbs shows sulfur dioxide concentrations decreasing as the plume ages and disperses (from right to left)*

were successful with one balloon tracking the elevated sulfur dioxide for nearly an hour as it was carried up Mt. Kilauea by catabatic winds (Fig. 3). After flights of two hours and five hours respectively, both balloons were recovered on land and returned to the laboratory for later reuse in the Arctic.

IV. Conclusion

Recent development of the CMET balloon platform has increased its capability, lowered its cost, and contributed to studies of atmospheric transport and transformation. Detailed analysis of the unique flight data and associated manuscript preparation are currently underway. Additional development of the CMET balloon is continuing with a focus on real-time characterization of pollution dispersion, in situ measurements of turbulence and trace species, and improved performance in harsh environments.

Acknowledgments

This work was supported by the Atmospheric Chemistry Program at the National Science Foundation (NSF), the Norwegian Institute for Air Research (NILU), the Targeted Winds Program at the National Atmospheric and Oceanic Administration (NOAA), the Climate Change Research Center at the University of New Hampshire, the Alfred Wegener Institute for Polar and Marine Research (AWIPEV), Andoya Rocket Range. I am grateful to the many colleagues who participated in the field studies without whom this work would not have been possible. These include Thomas Hartley, Rahul Zaveri, Adam Durant, Andreas Stohl, Lars Hole, Robert Talbot, Huiting Mao, Sibyl Brunner, Pamela DeAmacis, Indira Deonandan, Mauricio Estrada, Oscar Martinez-Antonio, Gaston Contreras-Jiménez, David Greenberg, Frank Flocke, Sasha Madronich, and the pilots and crew of the NCAR C130 and the organizers of the MILAGRO campaign.

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