GET SMART: USING INTELLIGENT BALLOONS IN CLIMATE RESEARCH

A research balloon capable of maintaining its flight through intelligent altitude adjustment is not only a distinct possibility but a proven fact. During the past six years, the authors have designed, flown, and evaluated three versions of this evolving balloon, demonstrating the craft's feasibility and also its great value in climate research.

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The "most intelligent" of the smart balloons, this craft features a larger transponder and shell to compensate for condensate on the balloon surface. Photo by Randy Johnson, with support from the University of Hawaii

Global warming and *greenhouse gases* are familiar terms of late, spurred by an international sense of urgency to comprehend the effect of human activity on the earth's climate. Because climate change may cause some regions to become more arid while plaguing other areas with increased floods, heavier snowfall, or more severe storms, the ability to accurately predict regional weather has tremendous economic implications.

The complex role that microscopic particles or *aerosols* in the atmosphere play in the dynamic global climate system is little understood yet represents an important component. Some scientists believe that an anthropogenic increase in aerosol in the atmosphere is cooling the earth's surface, counteracting, to an extent, the warming associated with increasing greenhouse gases. Calculating aerosol's climatic effect is difficult, however, because of a lack of globally distributed data and an incomplete understanding of how gas emissions relate to particle formation and growth in both clean and polluted air masses.

Since 1991, we have been constructing special atmospheric research balloons at the National Oceanic and Atmospheric Administration/Air Resources Laboratory/Field Research Division and at the University of Hawaii. In this article, we will discuss the evolution of our *smart* balloon, which can adjust its buoyancy to maintain flight in an air parcel of interest. This balloon system acts as a marker in the air mass by communicating its GPS position to a research aircraft. Scientists then use the GPS information to position the aircraft, which is filled to capacity with scientific instrumentation, near the balloon to sample the marked air mass as it moves with time. The collected data provide valuable insight into the growth of aerosols in the atmosphere and their influence on clouds and solar and terrestrial radiation.

The availability of affordable GPS receivers has enabled us to develop a system to track a low-altitude air mass anywhere in the world. We have flown three versions of our balloon (see Figure 1) in atmospheric chemistry field experiments at different sites around the globe in 1992, 1995, and 1997. The results have been exciting — with each generation, our balloons have become much more capable.

SOMETHING IN THE AIR

We are participants in the International Global Atmospheric Chemistry (IGAC) program, which is dedicated to understanding the chemical, physical, and radiative properties and processes of atmospheric aerosols. Researchers worldwide are participating in a series of IGAC experiments designed to provide the necessary data to support these research goals.

Given the complexity and scope of climate research, scientists must obtain a broad range of measurements. These observations may include concentrations of trace gases (for example, ozone or sulfur dioxide), aerosol size distribution and composition, cloud-drop size distribution, and radiation, as well as a suite of meteorological variables (such as temperature, pressure, and relative humidity). Researchers then use the resulting data sets to test regional and global atmospheric chemistry and aerosol models and thus produce more accurately assess the climatic effect of aerosols. The end result will be more precise climate-change predictions.

LAGRANGIAN EXPERIMENTS

A frame of reference that moves with the air is a natural choice for aerosol studies. This reference frame is commonly called *Lagrangian* after the inventor, French mathematician Joseph Louis Lagrange (1736–1813). A Lagrangian strategy offers distinct benefits over studies in which measurements are made only at fixed sites. Researchers can concentrate measurement resources, such as a research aircraft, in a moving air volume.

PHOTOS BY STEVEN BUSINGER

The effect of aerosol on incoming sunlight is apparent in this scene (above) of suspended African dust from the Sahara Desert. The question is, how does it affect climate?

The quality of the sunlight illuminating the photograph (right) of Santa Maria, is indicative of the relative lack of aerosol in the clean air over the central Atlantic ocean. Such a site provides an ideal opportunity to obtain a baseline data set.

Because the mean wind in the Lagrangian reference frame is approximately zero, lateral flow in and out of the air volume is typically small, an important advantage when studying changing aerosol concentrations. Moreover, fixed sites in the ocean (such as ships) are very expensive. GPS technology provides an effective way of marking a moving air mass.

Conducive Conditions. To conduct successful Lagrangian experiments during our three projects, we paid careful attention to weather. Generally dry conditions, with a well-mixed lower atmosphere or marine boundary layer capped by a strong temperature inversion or stable layer, were ideal. During all three trials, a team of scientists and forecasters at an operations center closely monitored weather patterns and airflow trajectories using satellite imagery and numerical weather prediction models. To allow sufficient aircraft sampling time over a period of two days, the forecast trajectory of a chosen air volume had to pass close to a ship located upwind of the operations center. The trajectory then was forecast to pass near the operations center and move downwind slowly enough to stay in range of the scientific aircraft staging site.

Release the Balloons! The upwind ship served as the release platform for the balloons and also as an important data-gathering site during all our field programs. The limited deck space for balloon inflation and the added cost of larger balloons provided incentive to keep balloon size as small as possible. To minimize size, we also restricted payload weight and power usage. Following balloon release, we tracked the craft past and downwind of the operations center during a sequence of research flights. The Lagrangian strategy required back-to-back flights to permit near-continuous sampling over a two-day period, using two aircraft or a single plane with two crews.

During each Lagrangian experiment, a 2–4-person team launched multiple balloons to provide redundancy and information on atmospheric dispersion. Team members inflated the balloons and set the exact lift of each craft so that it flew at the desired altitude. While the balloons were being prepared, other members checked the transponders for proper operation and configured the balloon-operating parameters.

THE PRECURSOR: ASTEX/MAGE

We designed our first balloon for the Atlantic Stratocumulus Transition Experiment/ Marine Aerosol Gas Exchange (ASTEX/ MAGE) field project, which took place June 1–25, 1992, near the Azores Islands off the coast of Portugal. In addition to examining the biogeochemical budget cycles of various chemical species and the chemical composition of the atmospheric aerosol, the project goal was to investigate the processes controlling the life cycles of marine stratocumulus clouds in the relatively unpolluted marine atmosphere over the north Atlantic Ocean.

A Bright Idea. We had begun researching the possibility of integrating low-cost GPS receivers into a small balloon transponder in September 1991. At this time, the GPS constellation was sufficient to provide continuous latitude and longitude information, but occasionally only three satellites were in view, preventing the receiver from supplying continuous balloon elevation data. During those periods, we assumed altitude was constant. By January 1992, we started designing the balloon with financial support from the U.S. Office of Naval Research.

We made every effort to use off-the-shelf subsystems and components. Our platform was a well-proven, 1.6-cubic-meter tetroon. The balloon was tetrahedral in shape (hence, the term *tetroon)* for easier construction and featured a constant-volume design.

To save design time, we opted for an inexpensive, five-channel, L1, C/A-code GPS receiver board that provided standard NMEA message strings. An inexpensive and unmodified ultrahigh-frequency radio transmitter and modem transmitted balloon position data. A single transmission frequency served all transponders.

A low-power microcontroller with built-in battery backup on a small circuit board managed system power, gathered and saved position data, and controlled the radio-frequency transmitter. When not in use, the microcontroller transitioned into a power-saving *sleep* mode. A small power supply and interface board connected each subsystem to the microcontroller, allowing us to switch power to each subsystem on and off. The power supply was a high-efficiency, switching regulator that converted unregulated battery

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Up, up, and away! — team members release Lagrangian marker tetroons during ASTEX/MAGE.

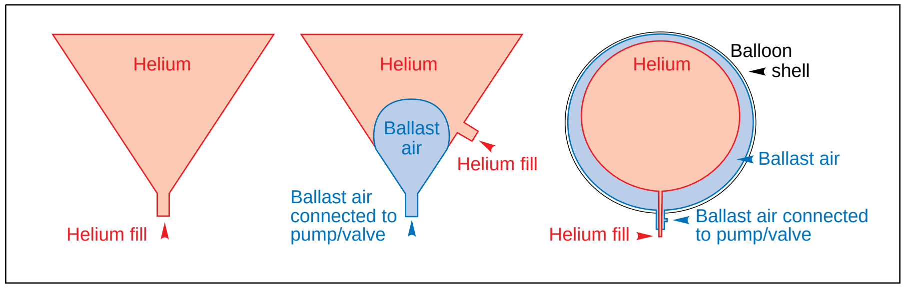

Figure 1. (from left to right) The first balloon, a precursor to the smart balloon, was a simple, tetroon design. Also a tetroon, the second balloon was the first "smart" generation, meaning that its lift was adjustable depending on environmental conditions. The pump/valve and ballast bladder allowed variation in balloon lift. The second-generation smart balloon featured a larger-volume spherical shell and increased variable-lift range.

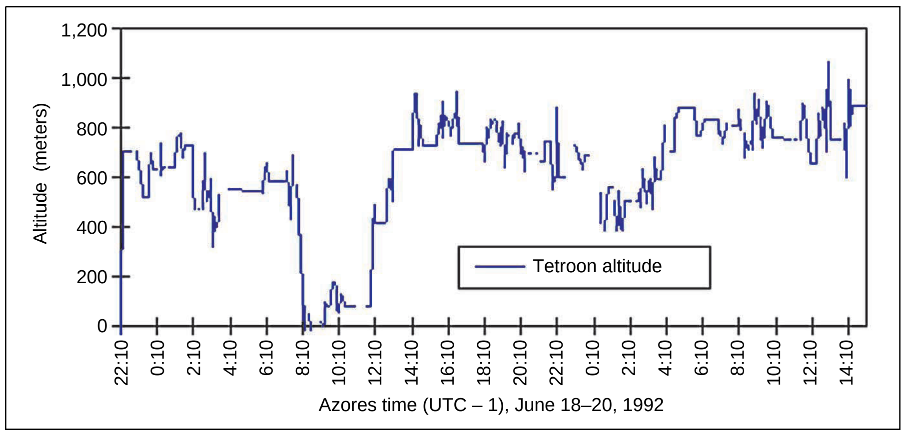

Figure 2. In this graph of the height of the tetroon markers as given by GPS data during the second ASTEX Lagrangian experiment, the balloon is seen to sharply dip. This was caused by environmental conditions that the balloon was not designed to adjust for, causing the craft to descend below the chosen flight level.

power to the necessary 5 volts.

Each transponder transmitted a distinct address that enabled us to identify data from different transponders flying at the same time. The address also assigned each transponder a unique window of time (once every 5 minutes) to transmit without interfering with other transponders. Time data from the GPS receiver were instrumental in keeping the transponder clocks synchronized.

First Flight. The operations center was on a remote island, Santa Maria. On the launch ship, we inflated five tetroons, carefully ballasted them for a flight level of about 1 kilometer, and secured them on deck. We placed radio receivers with data demodulators and a notebook computer on the aircraft to receive transmissions from the balloon transponders every five minutes. Once we released the tetroons, we could not change their buoyancy or flight level. After sequentially releasing all the tetroons, the GPS data from the tetroons were monitored by an aircraft observer who relayed the positions to the mission scientist and pilot.

That Sinking Feeling. The GPS transponder was mostly successful, enabling us to track air movement in the marine boundary layer, the lowest atmospheric layer directly affected by the underlying ocean surface. Though we planned the launch to coincide with a forecasted high-pressure ridge that was relatively stable and dry, the tetroon encountered significant marine stratus and precipitation, as can be seen from the elevation plot in Figure 2. The craft stayed within the marine boundary layer, but the altitude was erratic because of precipitation loading on the tetroon's exterior and of convective activity in the area.

These results demonstrated the need to control balloon lift in response to changing atmospheric conditions. We lost tetroons either in the ocean or outside the desired altitude range because of changing meteorological conditions. Future GPS transponders would clearly benefit from balloon altitude control functions to maintain the craft within the desired altitude range.

FIRST SMART BALLOON: ACE-1

Right after the ASTEX/MAGE experiment, we began investigating possible ways to incorporate altitude control and to create, in effect, a "smart" balloon. In early 1995, funded by a grant from the National Science Foundation, we pursued our work for the first in a series of IGAC Aerosol Characterization Experiments (ACE). We were faced with a short development time, with the field deployment beginning only 10 months later. Fortunately, we could base the ACE-1 smart balloon on much of the ASTEX/MAGE GPS transponder hardware and software.

Get Smart. Given the expected greater weight of a smart balloon transponder, we settled on a 4.25-cubic-meter tetroon containing an air ballast bladder, which is shown in Figure 1. This design enabled the tetroon to change its lift or buoyancy to maintain altitude during several warm/cool or wet/dry cycles. A low-cost analog barometric pressure sensor measured ambient air pressure, which is proportional to altitude in the lower atmosphere. Although by this time the GPS constellation was fully operational, selective availability made its elevation determinations less accurate and reliable than that of the barometric sensor (±25 meters at the altitude of interest).

When the balloon strayed outside preset pressure/altitude limits, valves and a small, low-powered pump moved air in or out of the internal ballast balloon, causing the balloon

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The National Center for Atmospheric Research (NCAR) C-130 aircraft rests on the tarmac of the Hobart International Airport, in Tasmania, during ACE-1. When fully fueled, the NCAR C-130 can carry a payload of 13,000 pounds including instruments, scientists, and flight crew.

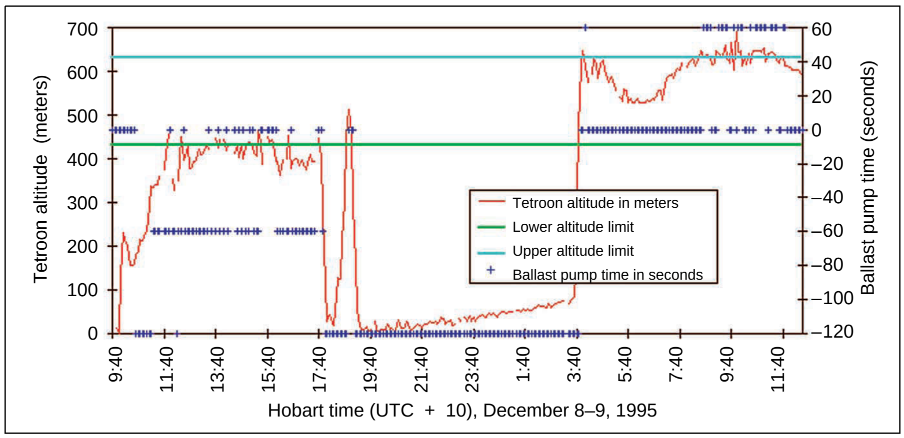

Figure 3. This figure shows a time series of altitude versus ballast pump time from the ACE-1 Lagrangian smart tetroon, December 8–9, 1995. The sharp drop in altitude indicates that though the ballon lift was adjustable, the precipitation loading exceeded the balloon's designed lift range.

to rise or fall as needed. We set the density adjustment range at ±160 grams, which we expected would be sufficient to compensate for changing air temperature, barometric pressure, and surface condensation. We also added analog transducers to record air temperature, relative humidity, tetroon internal pressure, and tetroon surface wetness to further our understanding of the flight behavior of the smart tetroons.

A smaller, lighter, and lower-power five-channel, L1, C/A-code GPS receiver reduced transponder battery power and weight. We modified the microcontroller software because the GPS unit used a proprietary binary data string for position and time. A low-power microcontroller board added an analog-to-digital converter, but because it used the same type of microprocessor chip as the earlier board, we were able to reuse much of the previously developed software, merely modifying it a little to accommodate the pump and valve control functions.

Southern Sailing. ACE-1 took place in the minimally polluted marine atmosphere south of Australia, during November 15-December 14, 1995. The operations center was at the Hobart International Airport on the island of Tasmania. With the limited deck space, inflating more than one tetroon at a time was not possible; thus, we filled and released them one by one, with one or two hours between launches.

Putting on Weight. We conducted two successful Lagrangian experiments, tracking the tetroons for a little more than 24 hours. The design changes were for the most part effective, enabling the balloons to compensate for almost all atmospheric conditions. The exception was when precipitation or condensation accumulated on the tetroons' flat upper surface, causing the tetroons to descend (see Figure 3). Subsequent lab simulations of condensation on the polyester shell showed an increase in weight of as much as 900 grams, exceeding our projected ±160 grams. Our work was cut out for us: The next balloon would need a greater dynamic lift range to overcome this additional weight.

SECOND SMART BALLOON: ACE-2

In early 1996, just after the ACE-1 field project, we started working to solve this problem. The answer lay in a larger ballast air mass and a spherical design to shed water. Increased ballast, however, produces higher internal pressure, which, in turn, necessitates stronger material to withstand the added force on the balloon shell. After testing several possible materials, we settled on an ultra-high-strength fabric. The fabric offered low elasticity as well as a low thermal coefficient of expansion, which enabled the new balloon to maintain a very stable enclosed volume. Using this fabric in a spherical shell with two inner bladders allowed us to increase air ballast to about ±1,200 grams and maintain outside dimensions similar to that of the ACE-1 tetroon (see Figure 1). We targeted this latest balloon for deployment in the June 1997 ACE-2 field program in the Canary Islands, designed to study polluted air emanating from Europe.

In Command. We added an exciting new feature to the ACE-2 balloon, namely the two-way communication capability, enabled by adding a radio receiver to the balloon and a transmitter on the research aircraft. We could now change balloon-operating parameters — such as lift — after launch by transmitting a message to the balloon through the notebook computer on the aircraft. Moreover, configuring the transponder to transmit only when the aircraft radio system was in contact with the balloon saved transponder power.

Getting Smarter. The larger balloon and desired shorter response time for changing conditions called for higher pumping capacity. Two pumps (from the ACE-1 project) provided a capacity of 20–25 liters per minute and could increase the balloon weight at a rate of 20–25 grams per minute. Lab tests indicated that this rate would accommodate the maximum rate of water evaporation on the balloon's skin.

A single large pinch-off valve on a piece of latex rubber tubing released air faster. A small gear motor, running in forward or reverse for a few seconds, opened or closed the valve. The pressure inside the balloon forced the ballast air out of the balloon. The release rate, even at low balloon pressures, was several times the pumping rate. This allowed the balloon to quickly increase lift.

As with the previous balloons, minimizing total transponder weight, design time and cost, and power consumption was critical. To add the changes and new features that we wanted — for example, making meteorological measurements such as balloon temperature and solar radiation data — the transponder, like the balloon, would have to be an all-new design.

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Atop El Teide in Spain, researchers had a bird's-eye view of clouds marking the top of the marine boundary layer during ACE-2. More than 140 years ago, the mountain also played a role in climate research. In 1856, C. Piazzi-Smyth, a British astronomer, carefully measured temperature and moisture as he ascended El Telde's slope. His measurements resulted in the first published description of the stable trade-wind inversion — a marked increase in temperature with height, which characterizes the dry stable air that caps cloudy marine air nearer the ocean surface.

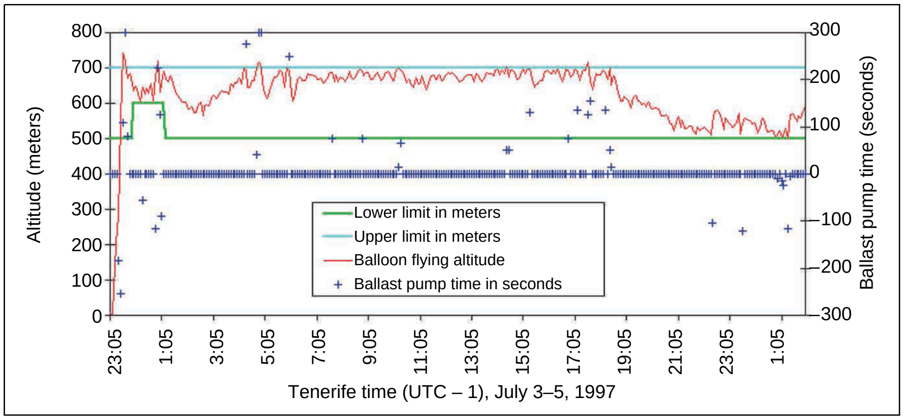

Figure 4. As the graph shows, the latest smart balloon maintained its level of flight quite well, staying within the prescribed altitude range.

Fortunately, a common low-power data logger with versatile control and data storage subroutines helped reduce the hardware and software development time from weeks or months to a few days. The dataloggers also contained built-in hardware monitoring and control, saving even more time.

Advancements in GPS technology also benefited us greatly. Whereas the earlier GPS receivers had required 40–60 seconds to acquire a new position, our new eight-channel, L1, C/A-code GPS unit acquired a fresh position in just 15 seconds from a warm start, thus reducing GPS receiver energy consumption by two-thirds. Finally, fabricated battery packs with AA lithium batteries provided the best power-to-weight ratio, enabling three-day operation.

Dusty Flying. In June and July 1997, we deployed our second-generation smart balloons over the Atlantic Ocean between Portugal and the Canary Islands. ACE-2 objectives were to conduct a series of aerosol characterization and process studies over the North Atlantic Ocean with a focus on anthropogenic aerosols from Europe and desert dust from Africa.

The operations control center was at the north airport on the island of Tenerife. Before the start of the first Lagrangian experiment in this round of experiments, we tested one of the new GPS transponders by placing it in a car and ascending El Teide (elevation 3,700 meters or 12,044 feet), the highest mountain in Spain. A research aircraft successfully tracked our rental car from the air, confirming the new transponder's range and reliability. Balloon preparation and launch procedures were similar to those followed in ACE-1.

A Well-Rounded Balloon. Figure 4 shows the altitude and ballast pumping time for a balloon tracked for a little more than a day. We set the altitude range between 400 and 600 meters and, for a short time at the beginning of the test, raised the lower altitude range to 500 meters. Notice that when the balloon exceeds the altitude range setting, it adjusts the ballast to move back inside the altitude window of operation. We experienced no problems with ballast range capability, even in the evening when the surface moisture sensor revealed substantial condensation accumulation.

Overall, the smart balloons in the ACE-2 Lagrangian experiments performed very well. We tracked six of eight balloons after releasing them from the ship; the remaining two, damaged during launch, were not tracked. The command capability provided us with operating flexibility unavailable on previous experiments. The balloon altitude feature functioned flawlessly, and we believe that changes in the control algorithm can provide even better performance.

UNFETTERED FUTURE

The recent completion of the GPS satellite constellation and availability of small, low-power, low-cost GPS receivers have made the smart balloon a reality. Starting with inexpensive constant-level tetroons during ASTEX/MAGE and evolving to the relatively sophisticated design of the ACE-2 smart balloon, the capabilities of the balloon platform have risen with time. These capabilities and their economical cost make the smart balloon an attractive platform for a range of applications in atmospheric chemistry and mesoscale meteorology. Future improvements in the design and deployment strategy are focused on extending the smart balloon platform to investigate the energetics of destructive storms. For example, to provide critical protection from the elements, we are considering changing the transponder design to enable it to fit inside the balloon shell.

Preliminary results of the complex IGAC field experiments are just beginning to emerge and should help global climate models more accurately account for the effect of aerosols and, thus, reduce the overall uncertainty in predicting the climatic impact of anthropogenic aerosols. For further information on this fast-changing aspect of our story, visit the IGAC home page at <http://web.mit.edu/afs/athena.mit.edu/org/i/igac/www/index.html>.

ACKNOWLEDGMENTS

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MANUFACTURERS

The authors used an OEM GPS board from **Magellan Systems** (Sunnyvale, California) in ASTEX/MAGE, a MicroTracker board from **Rockwell** (Cedar Rapids, Iowa) in ACE-1, and a Lassen-SK8 board from **Trimble Navigation** (Sunnyvale, California) in ACE-2.