Probing the Atmosphere from Balloon Platforms

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Abstract

High-altitude balloon-borne platforms offer a number of advantages for atmospheric measurements. They can be used to carry payloads ranging from a few kilograms to several tons, consisting of extractive, in situ, and remote sounding instruments. They typically reach float altitudes of 35 to 40 km, allowing the atmosphere to be probed from above rather than looking up through the dense lower atmosphere, as must be done with ground-based measurements. Height-resolved measurements of atmospheric properties can be made on ascent, or from float using spectroscopic remote sounding techniques that scan through a range of elevations in solar occultation or limb-viewing mode. Customized balloon flights, such as valve-controlled slow descent, double ascent, or long duration flights, can be designed to match the scientific requirements. These enable instruments to make measurements over periods ranging from several hours to several weeks. This paper summarizes some of the capabilities, advantages, and disadvantages of using balloon-borne platforms to probe the atmosphere. The MANTRA (Middle Atmosphere Nitrogen TRend Assessment) series of high-altitude balloon flights, which were undertaken from Vanscoy, Saskatchewan between 1998 and 2004, are used to illustrate some of these points, and future prospects for ballooning in Canada are discussed.

1. Introduction

Balloon platforms offer excellent opportunities for scientific exploration, particularly for atmospheric observations that look through the atmosphere, and for astrophysical observations from above the atmosphere. They provide a vehicle for technology development, and can be used for testing prototypes of satellite instruments. They are valuable for satellite validation, as they can provide height-resolved atmospheric measurements necessary for assessment of similar satellite observations. In addition, they enable the training of scientific and technical personnel – the next generation of space scientists.

Scientific ballooning began just over two hundred years ago, in 1803, when the first scientific balloon flight took place – it reached an altitude of 7,400 m and was used to measure electricity in the air [1]. One year later, Joseph Louis Gay-Lussac measured the composition of the air from a balloon. The first aerial photograph was taken by Gaspard Felix Tournachon in 1858, from a tethered balloon floating at 80 m. Atmospheric measurements also continued to be made from balloons, and led to the discovery of the stratosphere in 1902 by Léon Teisserenc de Bort, who used data from 236 balloon flights made near Paris. An altitude record was set by Auguste Piccard in 1931; he reached 16 km in a spherical, airtight, metal cabin suspended from a hydrogen-filled balloon of 14,000 m^3. Four years later, in 1935, Orvil Anderson and Albert William Stevens ascended to 22,080 m, collecting air samples to determine the vertical structure of the atmosphere. See Nishimura [2] for further discussion of scientific ballooning in the 20th century.

The modern era of scientific ballooning may be said to have started in the 1950s and early 1960s. In 1961, the National Science Foundation in the USA began a balloon program that became the National Scientific Balloon Facility (NSBF). This moved to Palestine, Texas in 1963, and subsequently launched 2500 balloons in 25 years, with a 90% recovery rate. NSBF was renamed the Columbia Scientific Balloon Facility (CSBF) in 2006, and is a NASA facility managed by the Physical Science Lab of New Mexico

State University. The contract to manage the facility is administered by the Balloon Program Office at Wallops Flight Facility of the Goddard Space Flight Center [3,4]. Currently NSBF launches about 25-35 balloons a year.

Building on its historical role as the home of ballooning, France saw the first balloon flight by the Centre National d'Etudes Spatiale (CNES) in 1972. France continues to have an active balloon program, particularly in atmospheric science measurements, currently launching about 50 balloons a year [5,6]. A number of other countries also have active ballooning programs, including Japan, Brazil, India, and Sweden [7,8,9].

Here in Canada, the first balloon-based atmospheric measurements used infrared spectrometers to study the Earth's airglow (see [10,11] and references therein). Noxon and Vallance Jones [12], working with the Canadian Armament Research and Development Establishment (CARDE), measured hydroxyl emission from a balloon launched in 1960. Further balloon-borne measurements of OH followed (e.g., [13,14]). Meanwhile Gush and Buijs [15] were the first to detect the 1.27 micron band of O_2 in the nightglow using a balloon-borne Michelson interferometer that was flown in September 1962; the balloon was launched from Valcartier, Quebec, and reached 27,400 m [16]. This instrument was subsequently reflown [17,18,19], while Evans *et al.* [20] also observed the 1.27 micron O_2 band using a filter photometer flown on a series of balloon flights from Saskatoon and Churchill. See references [21,22] for a review of some of the early history of ballooning at CARDE, the University of Saskatchewan, and the National Research Council.

In the 1970s and 1980s, the Atmospheric Environment Service of Canada led the Stratoprobe series of balloon flights that included measurements of NO_2 and HNO_3 that predate the onset of stratospheric ozone depletion. These campaigns contributed to our understanding of the stratosphere and included early estimates of the northern hemisphere mid-latitude odd-nitrogen budget (see [23] and references therein). The Stratoprobe measurements also provide a useful benchmark against which current measurements can be compared to examine the possibility of detecting long-term changes.

2. The MANTRA Balloon Campaigns

The MANTRA (Middle Atmosphere Nitrogen TRend Assessment) series of high-altitude balloon flights were undertaken to investigate the odd-nitrogen budget of the northern hemisphere mid-latitude stratosphere, building on the earlier Stratoprobe balloon campaigns [23]. Four late summer campaigns have been carried out, all from Vanscoy, Saskatchewan (52°N, 107°W). Each balloon carried instruments to measure vertical concentration profiles of a suite of stratospheric trace gases and made observations from a float altitude of about 35 km for one day. Several of these instruments were flown 15-20 years ago during Stratoprobe and therefore provide a link to historical data predating the onset of ozone depletion. These campaigns have been supported by the Canadian Space Agency and the Meteorological Service of Canada (all flights), CRESTech (1998), and NSERC (2002, 2004). The MANTRA Science Team includes personnel from the University of Toronto, Environment Canada, York University, and the University of Waterloo, as well as international partners from the University of Denver, and the Service d'Aéronomie of CNRS (Centre Nationale de la Recherche Scientifique). Payload and launch support was provided by Scientific Instrumentation Limited of Saskatoon.

The scientific objectives of the MANTRA project are:

(1) To conduct a series of balloon flights, each carrying a suite of instruments to measure vertical profiles of the key stratospheric species that control the mid-latitude ozone budget, particularly species in the NO_y, Cl_y, Br_y, and HO_x chemical families, along with dynamical tracers and aerosols.

(2) To combine these measurements with those obtained from similar northern mid-latitude campaigns of the past 20 years, in order to quantify changes in the chemical balance of the stratosphere, with a focus on the odd-nitrogen budget.

(3) To compare measurements of the same species recorded by different instruments on the balloon, and perform an intercomparison and assessment of the old and new measurement techniques.
(4) To use the measurements for validation and ground-truthing of satellite measurements, including those made by instruments on the Odin, SCISAT-1, and ENVISAT platforms.

Four campaigns have been conducted. MANTRA 1998 was the first Canadian launch of large high-altitude balloon in about 15 years. It involved the flight of an ambitious payload that combined older and newer instruments. A total of eight flight instruments, three ground-based instruments, and aerosol backscatter and ozone sondes were deployed. MANTRA 2000 was primarily an engineering test flight of a new pointing control system, although four instruments were flown, and aerosol backscatter and ozone sondes, and three ground-based instruments also took part. With MANTRA 2002, another large payload was assembled, consisting of nine flight instruments, with accompanying sondes and four ground-based instruments. MANTRA 2004 was a seven-week campaign, which involved two launch attempts of a payload of 11 flight instruments, a SAOZ-BrO flight, 21 ozone sonde flights, and six ground-based spectrometers that made 43 days of measurements.

3. Balloon Capabilities: Advantages and Disadvantages

Balloons offer a number of advantages as observation platforms. They can carry payloads ranging from a few kilograms to several tons. They can carry a variety of payloads, including sampling, in situ, and remote sounding instruments. They can fly at altitudes from near the surface to the upper stratosphere. For the latter, they can reach float altitudes of 40 km, which represent near-space conditions where 99% of the atmosphere is below the instrumentation. This is ideal both for probing the atmosphere through the thin upper layers, and for looking to space with minimal atmospheric interference.

Balloon observations of the atmosphere can be made on ascent or from float by scanning in elevation to obtain height-resolved measurements. Balloons provide observations of detailed processes on much finer spatial and temporal scales than is possible from the ground or from satellites. The duration of balloon flights can range from a few hours to several weeks, and they can be designed for special flights to match the scientific requirements, such as valve-controlled slow descent, long duration flights, and tethered flights.

The timescales for balloon missions are relatively short, typically taking from two to five years from concept to flight. Such missions allow testing of new instruments that may have little or no flight heritage. Balloon payloads are usually recoverable (typical recovery rates are 80-90%). Balloon programs are much less expensive than satellite programs, and have many applications, including atmospheric chemistry and dynamics, radiation, weather and climate, and astronomy and astrophysics.

Sadourny [6] states succinctly the advantages of balloons for atmospheric science:

> *"It can effectively be asserted that balloons have no substitute for:*
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> - *observations and measurements both in situ and by remote sensing, of ozone and atmospheric minor constituents, water vapour, ...in the range of 20 to 40 km, at all latitudes and all seasons,*
> - *studying the atmospheric dynamics as balloons can perform Lagrangian measurements within air tresses and their trajectories provide information at all scales and in wide range of altitudes on circulation, winds, turbulence and waves.*
>
> *Balloons are a complement to aircraft, satellites and ground based observations"*

Similar remarks can be found in the Australian Hansard, in discussions regarding an Agreement between the Governments of Australia and the USA on the Conduct of Scientific Balloon Flights for Civil Research Purposes [24]:

> *Mr Dunn [CSIRO] — Stratospheric balloons are an economical alternative to placing satellites in space on a permanent basis. 'Stratosphere' means at the edge of the earth's atmosphere — about 30-40 kilometres up. It is good up there for astronomy and astrophysics, environmental studies, meteorology and atmosphere studies. The advantages of the balloons versus, say, satellites and the shuttle—sending them up in NASA's shuttle—is that the payloads can weigh several tonnes underneath these balloons. The development time for the experiments to go up under these balloons is relatively short compared to what it would be if you were preparing for them to go up in a satellite or in a shuttle. So, it has some distinct advantages over the other two ways of getting experiments up into space.*

Balloon platforms also have some disadvantages. They depend on meteorological conditions at the launch site, as well as a range of logistical factors that can affect the launch and flight. Their trajectories depend on the winds at float altitude, making them less predictable than satellites. However, trajectory control systems are being developed that may make this less of an issue in the future [25]. Balloon flights tend to be of limited duration, generally about 100 days maximum, with most lasting less than three weeks. Zero-pressure balloons are limited by ballast/vent diurnal cycle, while superpressure balloons limited by leaks and UV damage, but long-duration superpressure balloons that use high-quality engineered seams and UV-resistant materials are under development [26]. Balloons do not provide a global view, although several concepts for global constellations of long duration balloons have been proposed. Finally, there are political issues associated with overflight of countries that may limit the range of balloon flights [27].

4. Technology and Training

Balloons provide an excellent platform for testing new instruments in the near-space environment, enabling the assessment of their suitability for satellite missions. These prototypes can later be used for validation and trouble-shooting of the satellite instruments and for complementary measurements. For example, the MAESTRO instrument on Canada's SCISAT-1 mission evolved from the Meteorological Service of Canada's SunPhotoSpectrometer [28]; both it and a balloon version of MAESTRO (MAESTRO-B) flew on the MANTRA campaigns prior to the launch of SCISAT-1. Similarly, MLS, TES, and HIRDLS on NASA's current EOS-Aura mission all have balloon heritage. To quote Jerry Fishman, leader of the Science Working Group of the Compton Gamma-Ray Observatory [29]:

> "*You would have to be foolish to fly a new detector on a satellite without first testing it under the conditions of a balloon experiment.*"

MANTRA provides an example of the use of balloon platforms for technology development. Four new instruments were first flown during the MANTRA campaigns: an acousto-optical tunable filter spectrometer, MAESTRO-B, an adaptation of the SCISAT-1 ACE-FTS instrument called PARIS-IR [30], and an airglow infrared radiometer. In addition, a new pointing control system was developed [31], and a ground-based UV-visible grating spectrometer was deployed during the balloon campaigns, enabling the evaluation of NO_2 vertical profile retrievals by comparison with the balloon measurements [32,33]. Several other instruments were refurbished for the MANTRA flights, and new retrieval algorithms were developed for the analysis of the resulting data: infrared emission radiometers [34], a Bomem DA5 Fourier transform spectrometer [35], the aforementioned SunPhotoSpectrometers, a Bomem DA2 FTS from the University of Denver [36], and an OH spectrometer [37].

Ballooning is also an excellent means for providing training of scientific and technical personnel. It offers students (and others involved) the opportunity to participate in all stages of the experiment from concept to hardware, measurements, and data analysis. It exposes students, post-doctoral fellows, and others to the achievement of a scientific goal (the science requirements) through the planning and execution of an experiment under conditions that involve tight schedule, weight, and power constraints.

They receive training in quality control and risk management, deployment of instrumentation in the harsh near-space environment, field operations, team projects, technical skills associated with launching stratospheric balloons, and experience in handling manageable data sets from a field experiment, often in collaboration with other members of the science team.

This relevance to training has been noted, for example, by Thomas A. Prince (Caltech Prof. of Physics, JPL Chief Scientist, LISA Mission Scientist) [38]:

> *"I can't imagine a better scientific training for experimental space science than the experience of building and launching a science payload on a balloon.* ***You directly experience all the important steps:*** *design to cost, schedule, weight, and power constraints; quality control and risk management; field operations; and reduction and analysis of data.*
>
> *The impact of the NASA Balloon Program goes far beyond the demonstration of technology and the direct science data that are produced -* ***the scientists who 'cut their teeth' in the NASA Balloon Program are very often the leaders of today's NASA space science missions and programs."***

MANTRA again offers an example of how ballooning can contribute significantly to training. A total of five B.Sc., nine M.Sc., and eight Ph.D. theses involving the MANTRA campaigns are either completed or in progress. More than 25 undergraduate research students have participated in various elements of the project, along with eight post-doctoral fellows and research associates, ten technical personnel, and additional engineering and technical personnel working with our industrial launch partner, Scientific Instrumentation Limited. 58 people were involved in the many aspects of the MANTRA 2004 campaign.

5. Conclusion: Future Directions for Ballooning

With recent advances in a number of technologies, the capabilities and reliability of scientific ballooning continue to improve. There have been technical advances in trajectory control, high-quality superpressure balloons, UV-resistant balloon materials, power systems, launch techniques, onboard storage, and telemetry (e.g., satellite links). In particular, significant effort is being put into the development of ultra-long duration balloon (ULDB) flights. The primary challenge for achieving such flights is the diurnal temperature cycle. During the day, solar heating causes the gas inside the balloon to expand, which can make it necessary to release gas to avoid floating too high. During the night, the cooling and resulting contraction of the gas requires the release of ballast to maintain altitude. Flight durations are thus limited by the availability of ballast and gas.

There are three types of long duration balloons currently in use. The first are the more traditional zero-pressure balloons that have been successfully used in long duration flights in the polar regions. For example, the 2004 Cosmic Ray Energetics And Mass (CREAM) flight recently set a flight duration of 41 days and 22 hours, circumnavigating the South Pole three times in Antarctic summer, when constant daylight allowed the float altititude to remain relatively stable at 37 to 40 km [39,40]. NASA/NSBF is also developing large (600,000 m^3) superpressure balloons to carry heavy payloads to high altitudes, with the goal being to carry 1600 kg to 35 km for flights up to 100 days [41,42,43]. These are sealed spherical ("pumpkin-shaped") balloons, made of durable composite plastic and fabric materials that can withstand high pressure during the day, and maintain pressure at night. Meanwhile, CNES has successfully developed and flown small superpressurized balloons that can carry payloads of 10-20 kg at altitudes of 18-20 km for several months; balloons have been flown over the Arctic, Antarctic, and equatorial regions, for the STRATEOLE/VORCORE/VOREDGE campaigns [44]. A third balloon design is that of the Montgolfiere Infra-Rouge (MIR), also developed by CNES; these consist of two separate hemispheres that allow the balloon to be heated by sunlight during the day and by upwelling infrared fluxes during the night. More than 40 such flights have been conducted, typically carrying a 60-kg payload to 18-22 km at night and to 28 km during the day; flights last about three weeks on average, but have been known to circumnavigate the globe three times over 69 days [45].

Looking further to the future, a number of proposals have been made for the deployment of global networks of hundreds of balloons for that would remain aloft for several years, making Earth observations that would complement and possibly even replace satellites. These include the Global Air-ocean IN-situ System (GAINS) [46] and the StratoSat^{TM} constellation [47]. Additional concepts include aerobots – steerable helium-filled blimps with possible landing and floating capabilities, which are of particular interest for planetary exploration, and the AEROCLIPPER. This is a small balloon that floats at about 50 m, in or just above the boundary layer; it is connected to a cable that is in contact with the surface of the ocean and is capable of covering long distances over several weeks for simultaneous sea surface and atmospheric boundary layer measurements [48].

Here in Canada, we are looking towards the future of ballooning and possible mechanisms, such as a new Small Payloads Program, to support new balloon missions. Ballooning provides an excellent return for the level of investment. There is always a trade-off between flight risk and resources; as currently implemented, ballooning is not supported and managed as a “space program” in Canada. Moving to a risk avoidance model where all systems are fully flight-tested requires a different approach from that used for MANTRA. It will require an increase in resources, i.e., people, schedule, money, and is likely to move some development out of universities and reduce student involvement. Currently, students and post-doctoral fellows get hands-on instrument experience – this is an important advantage of ballooning and should not be undervalued.

Our experience with MANTRA demonstrated the importance of maintaining momentum for an experimental program such as ballooning, and the need to build and retain expertise, meaning people, instruments, and launch support capabilities. The need for a significant investment in launch support equipment at Vanscoy is clear, as much of the existing equipment dates back 20-30 years, to an earlier era of ballooning. Managing launch subcontracts from universities has also been found to be difficult.

For the future, we would like to see broader involvement of Canadian universities in ballooning, continued collaboration between the Canadian Space Agency and Environment Canada, and science funding such as that formerly provided through NSERC’s Collaborative Research Opportunities Program. Ideally, Canada would move towards establishing a "program status" where there is a 5-10 year horizon for ballooning in Canada, with regular flight opportunities and some reasonable expectation of continuity. There should be willingness and flexibility to support riskier new instruments as well as proven ones. Such an approach would enable the development and implementation of new balloon technologies and capabilities, leading to greater opportunities for new and exciting scientific missions.

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