STRATOSPHERIC SATELLITES FOR EARTH OBSERVATIONS

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Very long-duration stratospheric balloon platforms could provide revolutionary Earth observations for a fraction of the cost of competing platforms, such as stratospheric unmanned aerial vehicles (UAVs) and airships and space satellites.

Observational systems in atmospheric science, operating from surface, manned aircraft, or satellite platforms, have advanced dramatically in the last 30 years. However, for observational systems to continue to advance, we must be open to revolutionary new possibilities just as our forebears were. Many new missions are very expensive and have had their development slowed. Now may be the opportunity to begin new revolutionary observational concepts, especially if they are very affordable.

One such concept is a stratospheric satellite (StratoSat) that flies safely above all dangerous weather systems and almost all air traffic. A StratoSat is a high-altitude, very long-life balloon whose flight path can be altered using aerodynamic lift aimed sideways from a wing suspended on a tether several kilometers below the balloon. The wing takes advantage of the large differences in wind speed between the altitudes of the balloon and the wing. At these altitudes StratoSats essentially orbit the Earth every 10–20 days, carried along by the pervasive and predominant zonal winds. Figure 1 illustrates a StratoSat system concept with a wing hanging down more than 15 km below. StratoSats could remain aloft for a year or more, steer themselves to maintain a desired latitude, and perform moderately targeted, coordinated in situ and remote sensing observations. StratoSats at 35-km altitude are in near-space, which means they have access to most of the atmosphere (>99%) below them and are exposed to the rigors of a harsh UV and thermal environment similar to space satellites. Their ground velocity is usually less than 40 m s^{-1} or <0.5% as fast as a satellite in low Earth orbit (LEO); thus, they can linger over atmospheric and oceanic struc-

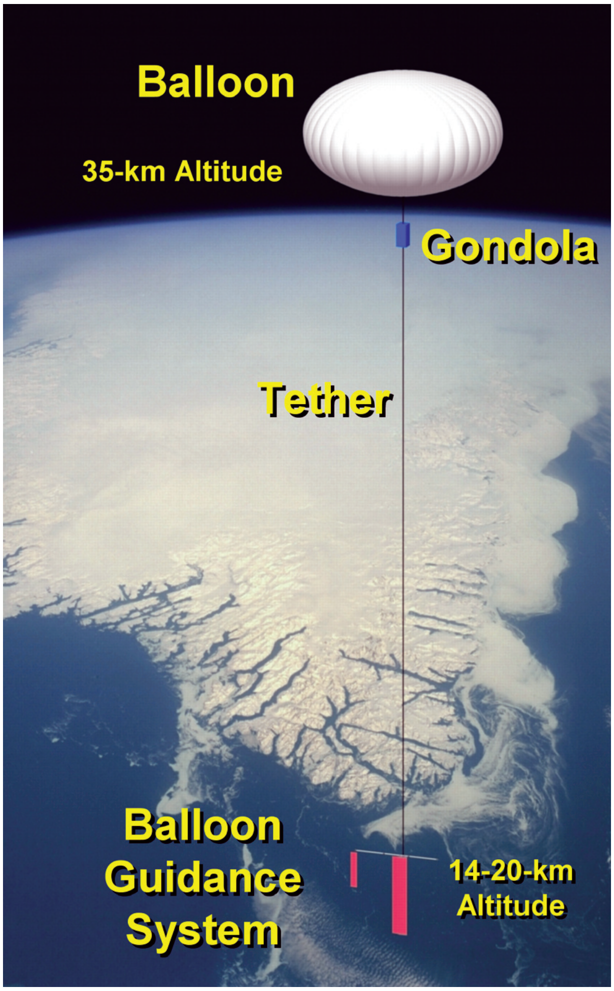

FIG. 1. StratoSat system concept illustrating a superpressure balloon and its science gondola along with its tethered guidance system hanging well below the balloon.

tures 200 times longer. Constellations of StratoSats, globally distributed, would not suffer the diurnal or sun-angle bias in observations that plague sun-synchronous space satellites.

Owing to their low cost, many StratoSats could be deployed to create constellations that offer a number of advantages over current surface, manned aircraft, and space satellite systems, including low total mission cost, synoptic coverage, and extremely heavy-lift capability. These constellations could become key components in a "sensor-web" architecture of cooperating, intelligent Earth observational systems contributing to at least four Earth science areas: Earth radiation budget (ERB), atmospheric chemistry, weather observations and forecasts, and geomagnetism. Key platform capabilities that would enable these observations have been defined by the National Aeronautics and Space Administration (NASA) as flight durations of 1 year; a payload mass of 200–500 kg; constant altitude flight between 30 and 35 km with the ability to make in situ measurements between 14 and 35 km; and a payload power of 1–2 kW (Pankine 2002a).

Balloons have a long history of Earth observations, beginning with the first human flights in France in the late 1700s and continuing to the current day, when they are used for routine weather prediction, atmospheric dynamics, and chemistry measurements. For 40 years space scientists have used heavy-lift balloons to carry instruments above the obscuring atmosphere, but these balloons were open to the atmosphere, carried ballast to stay at a constant altitude at night, and had to come down after a few days when the ballast ran out. Technologies are available today, or will be in the near future, that can revolutionize observations from balloon platforms; among these are the two key enabling technologies of UV-resistant, very long-life, sealed super-pressure balloons and balloon flight path guidance systems. In addition, there are several enhancing, or measurement-enabling, technologies, including network topology coordination, advanced and miniaturized in situ sensors and dropsondes, and GPS-guided parafoils for precision payload landing.

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International overflight restrictions could eventually become a consideration for StratoSats, although early flights could ascend from existing balloon-launch bases in McMurdo, Antarctica; Kiruna, Sweden; or Alice Springs, Australia, and make long flights over relatively uninhabited land and ocean. Initially, overflight could be handled, as it is now, on an individual country-by-country basis. For dense StratoSat networks, a number of pathways exist to obtain permanent global overflight permissions, including 1) incorporation of constellation systems into the Commission on Basic Systems framework of the World Meteorological Organization (WMO), 2) expansion of the 1992 Treaty on Open Skies, or 3) a new treaty based on the free use of the stratosphere for scientific purposes or on the need to monitor the troposphere for worldwide pollution control.

StratoSats are promising future observational platforms owing to their ability to satisfy some unique Earth observation needs, the relative maturity of the needed technology, and their low cost relative to space satellite, unmanned aerial vehicle (UAV), or airship platforms. Single StratoSat platforms would cost around one half to a few million dollars, depending on the scope of the science payload and the number of platforms needed. Space satellites, on the other hand, can cost several hundred million dollars because 1) they are expensive to launch and thus are made to be highly reliable and 2) they are often expensive, one-of-a-kind systems when they are designed to meet unique Earth science needs. A constellation of 100 StratoSats could give synoptic coverage for less than the cost of a single space satellite, which cannot provide synoptic coverage. Other advantages of StratoSats that make them inexpensive are a benign high-energy solar and galactic particle radiation environment and instruments that can be recovered for calibration, repair, and relaunch. As technology improves, StratoSats, unlike space satellites, can be easily upgraded through the recovery of old payloads and relaunch of new ones.

EARTH SCIENCE OBSERVATIONS. There are several potential applications of StratoSats for Earth

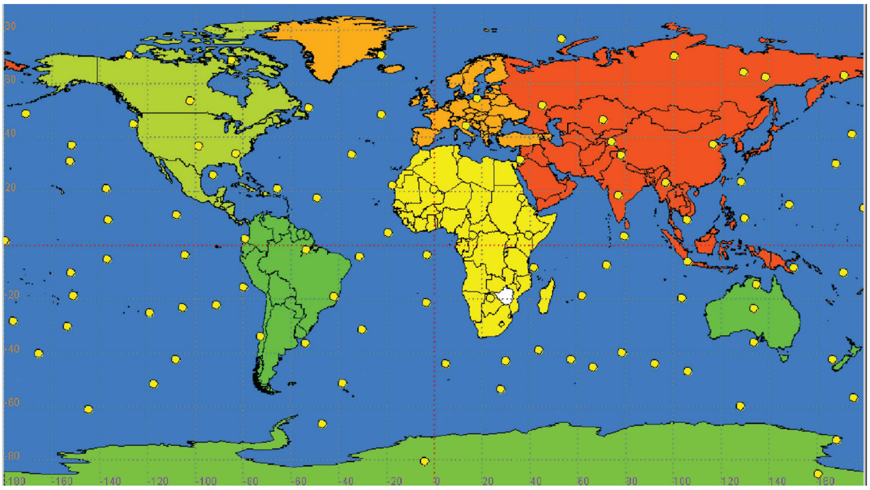

Fig. 2. Computer simulation of a constellation of 100 StratoSats (represented by yellow dots) working to maintain a uniform distribution by using artificial potential control laws. Shown is the global balloon distribution of StratoSats at 35-km altitude after 86 days of guided flight in historical stratospheric winds.

science observations. These Earth science applications include observations of the Earth's radiation budget, atmospheric chemistry, weather, and geomagnetic field phenomena.

Earth radiation budget. The Earth's climate system is driven by the geographic distribution of incoming radiation from the sun and emitted infrared radiation escaping to space. Radiative flux at the top of the atmosphere (TOA) and radiative flux divergence within the atmosphere are universally recognized as key drivers of climate change. After 40 years of retrieving these fluxes from single satellites or from small constellations, like NASA's ERB Experiment, serious uncertainties remain (Loeb et al. 2006, slide 13). Almost alone among the measurements that NASA retrieves from satellites, ERB remains essentially unvalidated; a long-term dataset of outgoing radiation fluxes has never been measured at TOA. StratoSats offer a perfect vantage point for these critical measurements and, unlike aircraft, they can remain aloft not just for hours or days (as is the case with UAVs) but for months or years. They can validate satellite retrievals and radiances because in situ measurements sidestep errors and assumptions inherent in remote sensing algorithms. Furthermore, StratoSats can measure flux directly. Flux is the integral of cosine-weighted radiance over all directions and can be measured directly with a balloon-borne flux radiometer at TOA, but ERB satellites can only measure radiance in one direction. Satellite-based ERB radiance-to-flux conversion algorithms have therefore become ever more complex over the past 40 years, but they still introduce a 4% averaged uncertainty in the instantaneous flux retrieval (Wielicki et al. 1995, Table 4). This 4% uncertainty in flux translates into a 2–3-K uncertainty in the effective radiating temperature of the underlying scene. These errors can be reduced to a climatically satisfactory point only by monthly averaging, at which point almost all the information on ERB dynamics has been lost.

StratoSats can measure ERB flux directly, without the assumptions inherent in radiance-to-flux conversions, and because of their rapid time sampling and low ground speed, they eliminate the need for time-interpolation assumptions; these assumptions are the two largest sources of uncertainty in satellite remote sensing of ERB (Wielicki et al. 1996). A constellation of 100 such balloons, as shown in Fig. 2, could provide assumption-free monitoring of dynamic changes in ERB fluxes over the entire globe, and for an estimated mission cost of $53 million to $144 million (U.S. dollars) (W. Wiscombe 2005, unpublished manuscript). A similar capability from LEO would require a six- to eight-satellite system. With StratoSats, one could, for the first time, observe dynamic changes in ERB from, for instance, volcanic eruptions or large dust storms; these phenomena are almost impossible to discern or study in monthly averages of ERB. Finally, StratoSats could potentially deploy radiation dropsondes to measure radiative flux profiles, a much-desired variable in climate models; their heavy-lift capability would allow them to carry hundreds of such dropsondes.

Atmospheric chemistry. Water vapor is the dominant greenhouse gas, and it has been known since the radiative–convective model studies of Manabe and Wetherald (1967) that the climate is exquisitely sensitive to stratospheric water vapor. Balloon constellations measuring stratospheric water vapor could address the question of what controls the water content of the stratosphere and its potential dependence on increasing CO_2 and other aspects of global change. An accurate continuous global water vapor measurement record in the upper troposphere and lower stratosphere and in the tropical tropopause layer is pivotal for unraveling the dehydration mechanisms proposed to control the water vapor budget of the stratosphere (Rosenlof 2003) and for understanding the radiative properties of the stratosphere.

Whether stratosphere water vapor is increasing or not is controversial. There are unresolved issues regarding the accuracy of the existing measurements and their long-term trends. There is no reasonable expectation, at least in the near term, that future satellite-based instruments will satisfy the stringent accuracy requirements necessary for making defensible stratospheric water vapor trend measurements in the region of the tropical tropopause where dehydration mechanisms are operative.

Because current aircraft cannot provide continuous or globally extensive measurements, one should consider constellations of StratoSats, which can provide direct measurements of water vapor and other atmospheric constituents in the region of the tropical atmosphere extending from about 14 to 35 km for a year or more. The profiling instruments can be integrated into a StratoSat's balloon guidance system and winched up and down like the Harvard atmospheric profiling experiments in the 1980s (Hazen and Anderson 1985) or they can be integrated onto a crawler that periodically descends and ascends the tether. Descending profiles can be relatively short (~1 hr to descend from 35 to 14 km) because they do not require expenditure of energy.

Weather phenomena. Space satellite measurements have increased over the last 30 years and now dominate the volume of weather observations, complemented by in situ observations taken at the surface and in the atmosphere. During this period, there have been significant advancements in space-based and in situ observations and both have had a positive impact upon forecast accuracy. In situ observations over oceans, polar regions, sparsely populated regions, and underdeveloped countries are relatively scarce. StratoSat constellations could fill in these data gaps by carrying canisters of thousands of high-tech dropsondes. In addition, StratoSats could be tailored to help test the potential forecast impact of new instruments and observing strategies designed eventually for more expensive space satellite or UAV deployment.

The growing accuracy of weather prediction since 1980 is primarily driven by advancements in 1) numerical modeling techniques, 2) data assimilation processes, and 3) substantial upgrades in computational infrastructure increasing resolution (Uppala et al. 2005). When the effects of the evolution toward a space-based observing system are isolated in this study, the improvements from the evolving observing system appear to have had a greater impact on the Southern Hemisphere. Research focused on the optimization of the global observing system, such as new complementary in situ observations proposed here, and continued efforts on the design of data assimilation would seem to be a wise investment given the substantial cost of the global observing system.

The importance of improving weather prediction to society led the 180 nations of the World Meteorological Congress to initiate a major international effort called The Observing System Research and Predictability Experiment (THORPEX) program to improve predictions of high-impact weather events on a 1–14-day time scale. THORPEX objectives, including "recommendations for implementing interactive forecasting systems and improvements in the global observing system," call for scientists to "test and evaluate experimental remote sensing and in situ observing systems and, when feasible, demonstrate their impact on weather forecasts" (Shapiro and Thorpe 2004). An interactive forecast system will deploy the right type of observations exactly when and where they are needed. Such a system could improve weather predictions for those events that have the highest societal effects.

The current adaptive mode employed for hurricanes and winter storms relies on dedicated research aircraft that deploy dropsondes at "sensitive" zones selected by their potential positive impact on forecast skill. One problem with remote and in situ measurements from aircraft is that observations from one or even two aircraft typically only provide partial coverage of these regions of forecast sensitivity with a relatively low number of observations, which limits the magnitude of forecast improvement obtained by such methods (Langland 2005). The sparseness of observations from aircraft is a direct result of their high cost of acquisition and operations.

StratoSats carrying dropsondes and/or remote sensing instruments may be a cost-effective option for such adaptive measurement streams. StratoSats are relatively inexpensive, and simulations have demonstrated that StratoSats can be guided to these relatively large "forecast sensitivity" zones where they are needed (Pankine et al. 2002b). If forecast improvements translated into decreases in the warning zone, reducing the uncertainty of a hurricane landfall by 100 miles would save $100 million (U.S. dollars) for just one episode (Adams 1999), which is the approximate cost of 40 StratoSats and their instruments. A network of StratoSats could become an integral part of a future interactive forecast system designed to improve weather prediction and its benefits to society.

Geomagnetism. Global and regional magnetic field measurements from StratoSats could lead to new understandings of the Earth's crust much as discoveries of midoceanic ridges and geomagnetic field anomalies on ocean floors led, in the 1960s, to the development of plate tectonics theory. Long-term measurements made over the North Pole and the South Atlantic Magnetic Anomaly can help monitor space weather, thus providing early warning for polar-orbiting space satellites, and offer new insights into the physics of geomagnetic field changes.

The advantages of using StratoSats are that observations at stratospheric altitudes enable the separation of various components of the Earth's magnetic field and the tying together of existing surface and satellite surveys. Because stratospheric altitudes (30–35 km) are comparable to the thickness of the crust (30 km), the whole depth of the crust can be "seen" from these altitudes. This is analogous to having Superman's X-ray vision of the crust, but in this case it is magnetic vision. Surface measurements by magnetic observatories only cover a small fraction of the Earth's surface.

Aircraft observations lack sufficient range, and measurements from ships are slow and expensive. Space satellite measurements are affected by ionospheric and magnetospheric disturbances and poor spatial resolution, and they require very high instrument sensitivity due to the weak field at orbital altitudes. Only StratoSats could make systematic measurements over hard-to-reach places over long enough periods of time. Magnetic studies from balloons are seen as important suborbital missions leading to new understandings of the Earth's crust (Space Studies Board 2007).

EMERGING TECHNOLOGIES. Two key enabling and several enhancing technologies will have a profound impact on StratoSat performance and capability. New, very long-life super-pressure balloons will enable flight durations of 100 days or more, and innovative balloon guidance systems will enable modest flight path control. In addition, there are several enhancing technologies that will enable some new missions, facilitate StratoSat network topology control, enable new measurement techniques, and increase safety and payload recovery reliability.

Super-pressure balloons. Conventional large scientific zero-pressure balloons are subject to buoyancy variations due to diurnal conditions that change the temperature, and hence the volume, of the buoyant gas. This change in volume requires ballast release at night and helium release in the morning to keep a steady float altitude. Ballast and helium release restrict flight durations to only a few days in moderate latitudes or up to about 40 or more days in polar summer conditions. Conversely, a super-pressure balloon is characterized by a fixed volume envelope. Once inflated, it rises to a constant density altitude and stays at that altitude without ballast or helium release regardless of diurnal conditions. A major technical challenge of super-pressure balloons is achieving the material strength required of the envelope because it is a pressure vessel. This level of this challenge is proportional to the diameter of the balloon; hence, small balloons are easier to develop than large ones.

The history of a very long-life, super-pressure ballooning extends back to the Global Horizontal Sounding Technique (GHOST) and the French Meteorological Experiment with Constant Level Balloons and Satellite Communication (EOLE) projects of the late 1960s and early 1970s (Lally et al. 1966; Morel and Bandeen 1973) when very small super-pressure balloons carrying lightweight electronic packages for meteorological research had flight durations that exceeded one year.

Today, zero-pressure balloons constructed of special polyethylene films fly above Antarctica in austral summer for more than 42 days in continuous and harsh solar UV radiation. From the perspective of UV degradation, this period of time is the near-equivalent of 84 days of operation in diurnal conditions. Given current super-pressure balloon materials, flight durations of 100 days are probably within easy reach. Advances in balloon materials, or their protection, are expected to enable flight durations of up to one year.

In one year a balloon would already be able to circle the Earth 20–40 times on a single tank of gas, so to speak; but to fly much beyond a year, methods and technologies will be needed for replenishing the buoyant gas that diffuses through the film or leaks through small flaws in the envelope.

NASA has been developing super-pressure, very long-life balloon technology in their Ultra-Long Duration Balloon (ULDB) Project for the last nine years to fly multiton sensors and telescopes to the "edge of space" for studying space science phenomena that cannot be studied well, if at all, from the surface (NSF 2008). After a successful small-volume (69,000 cubic meter) balloon flight in June 2000, full-scale volume balloons (520,000 and 594,000 cubic meters) were built and tested with the aim of achieving the goal of carrying 2700-kg instruments on 100-day flights above about a 33-km altitude.

Unfortunately, NASA has suffered repeated ULDB test flight failures of the large balloons over the last seven years. Several causes of these failures have been identified and analyzed by NASA, including inadequate designs that have resulted in partial envelope deployment, manufacturing flaws that have damaged gore seams, and film material property deficiencies that have not incorporated high-rate loading requirements (Cathey 2001; Smith and Cathey 2005; Cathey 2007). The underlying reasons for these failures appear to be that NASA balloon technology development has suffered from a lack of financial resources that has resulted in hasty system scale-up, an early focus on a single design concept, insufficient analytical performance modeling, insufficient material research, and design-induced manufacturing flaws and errors. In recent years, there has not been a consistent NASA funding line item for stratospheric balloon technology development. The hasty scale-up can also be attributed to the ambitious design goals that have focused on an extremely heavy payload capability driven by astrophysical science payload mass requirements, which require balloon sizes several times larger than the size needed for most Earth observations outlined here and 30 times heavier than previous generations of super-pressure balloon systems (Cathey 2007).

Fig. 3. Photograph of record-breaking ~200,000 m^3 volume ULDB test balloon at a float altitude of about 33.8 km shown soon after its McMurdo, Antarctica, launch on 28 Dec 2008 (Courtesy of M. Smith, Aerostar International Inc.; http://stratodude.blogspot.com/).

While the ULDB development picture has been discouraging, there are no technological showstoppers for Earth science balloons; the development problems can be overcome with adequate funding and a focus on smaller payloads and smaller balloons. As discussed earlier, a major technical issue of a super-pressure balloon is stress on the envelope. We know that very good Earth science could be accomplished with a balloon of half the diameter (or one eighth the volume) of the current ULDB program goal. Thus, a focus on developing these smaller balloons would reduce the stress on the envelope by a factor of 2, which is significant in terms of development challenge. The current ULDB development philosophy has appropriately scaled back on expensive, large-scale flight testing and increased reliance on small-scale ground and flight testing as well as on physical modeling (Cathey 2007; Wakefield 2007). With this new approach and, hopefully, an appropriate level of funding in the future, it is expected that NASA will eventually meet the unique challenges of producing ULDBs that can satisfy the needs of both the astrophysical and Earth observation science communities. To underscore this expectation, on 28 December 2008 from Antarctica NASA successfully launched, pressurized, deployed, and flew a small ULDB balloon (~200,000 m^3) of about the size that could be used for many of the Earth science applications discussed earlier.

Figure 3 is a picture of the fully inflated ULDB at float soon after launch. This ULDB test achieved more than 54 days of flight before its planned termination, thus breaking heavy payload endurance records.

Balloon guidance systems. After the balloon itself, a key technology for Earth science applications is flight path guidance. Without path guidance, computer simulations and operational experience show that ULDBs can drift to virtually any region in the Earth's atmosphere and tend to collect in regions of high vorticity where they remain trapped (Pankine et al. 2002b). Current stratospheric balloons can alter their altitude to seek favorable winds, but only at the expense of significant expenditures of resources and consumables (dropping ballast, compressing air, heating or releasing buoyant gases). These expenditures shorten the flights to only a few days when operating in day/night conditions. And even with this yo-yoing, the balloon can only go where the winds in a narrow range of altitudes can take it. Thus, StratoSats will need modest guidance systems that allow them to move relative to the wind at speeds of 1–5 m s^{-1}. Because stratospheric winds are typically much faster than this, guided balloons will not be able to station keep over a particular geographic position. However, simulations (Nock et al. 2007) have demonstrated that with wind forecasts from the current global numerical weather prediction programs, these modest path corrections over time can achieve remarkable results; not only can they guide balloons away from undesirable locations, such as high-population zones and toward science target zones or near landing sites, but they also maintain a roughly constant latitude (to create a "string of pearls" formation) or any other predefined network topology (for example, a uniform distribution as shown in Fig. 2).

Only two techniques for controlling the balloon trajectory have been put forward: first, a propeller-driven system, and second, passive "sailing" using a suspended wing as in Fig. 1. A propeller system would consume a large amount of energy to overcome the aerodynamic drag created by the balloon. Because the atmospheric density is so low at 35 km (150 times lower than at sea level), the propellers would have to be 5–8 m in diameter, dwarfing the size of the science gondola, and would require large amounts of chemical or electrical power (1–10 kW) for continuous operation even for modest latitudinal stationkeeping. Solar electrical power generation is limited to daytime operation and either batteries or fuel would be required to run at night (at the expense of payload). Batteries are heavy and trade off pound for pound against science payload, while fuel is a consumable that would severely reduce mission duration, just as ballast does for current stratospheric balloons.

Alternatively, passive sailing technology for trajectory modification has been developed (Nock et al. 2007) that takes advantage of the difference in horizontal wind velocity at different altitudes. The term "sailing" is used because the operation of a sailboat is a good analogy of how the guidance system works. The balloon is analogous to the sailboat keel, and the wing is analogous to the sailboat's sail. A sailboat takes advantage of the difference in densities between the air and water, whereas a balloon guidance system takes advantage of the different densities and wind speeds of air between two altitudes. Figure 4 shows a full-scale prototype of a winged balloon guidance system developed under NASA funding.

A winged balloon guidance system exploits the natural wind field variation with altitude available in the Earth's atmosphere (see mean zonal winds in Fig. 5) to generate passive lateral control forces on a balloon using a tether-deployed aerodynamic surface below the balloon. The wing is suspended several kilometers below the balloon on a tether. In the Earth's atmosphere, there is generally a vector wind difference between two altitudes, separated by a few kilometers, which results in a relative wind at the wing, allowing it to generate a lift force by use of a vertical rudder that changes the main wing's angle of attack. This lift force can be directed horizontally across the natural flight path of the balloon. This force is transmitted along the tether to the balloon, causing the balloon to drift across the winds at its altitude. Acting over a period of time, this small force (on the order of 100 N) can move the balloon hundreds to thousands of kilometers away from where it would have gone by simply drifting with the prevailing winds. An example trajectory simulation, displayed in Fig. 6, demonstrates guidance system performance in historical winds.

Fig. 4. A photograph of the full-scale mechanical prototype of a first-generation, single-winged balloon guidance system that was built and ground-tested under NASA funding. The main wing is 5.5 m in span with a 1.1-m chord.

The StratoSat wing usually hangs about 15 km below the balloon on a long tether, well above commercial airspace and above most military aircraft. For those few atmospheric chemistry mission scenarios that require in situ atmospheric sounding down to 14-km altitude (~46,000 ft), somewhat longer tethers or lower balloon altitudes are needed, along with

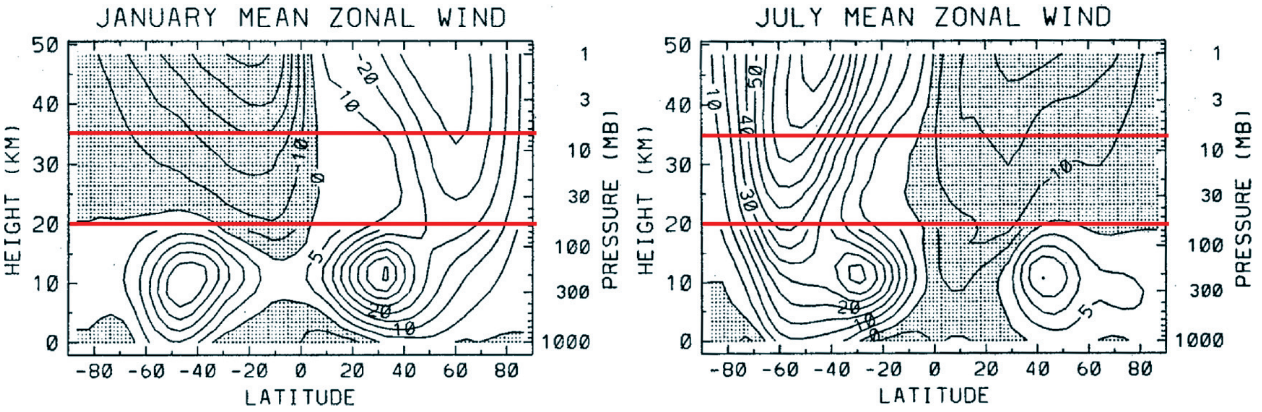

Fig. 5. Mean zonal winds as a function of altitude and latitude for (left) January and (right) July. The horizontal red lines represent the usual StratoSat balloon and winged guidance system altitudes. The relative wind at the wing is approximately equal to the difference between the winds at these two altitudes. There are two short so-called turnaround periods each year when the winds above about 20 km shift their zonal direction. This shift usually begins at the highest altitudes in the polar regions and evolves both equatorward and toward lower altitudes. These charts are from Randel (1992).

appropriate aviation notices that may be required to satisfy commercial and military airspace regulators.

Successful test flight experiments have been conducted (Nock et al. 2007), in windy conditions, of a 1/4-scale model balloon guidance system suspended below a blimp tethered to the ground (see Fig. 7). The winds simulated the relative wind conditions that the full-scale wing would see caused by the wind difference between a balloon at 35-km altitude and the wing at 20-km altitude. Several instruments mounted on the model provided quantitative measurements, including the actual forces applied to the tether. These tests were very successful in demonstrating that the full-scale system will perform as predicted in the Reynolds number regime in which the full-scale system will operate. In addition, a full-scale mechanical prototype has been built as shown in Fig. 4. Once the flight sensor, control, power, and winch-down systems have been designed, fabricated, and integrated into the prototype, a full-scale test can be carried out using the currently available balloon systems.

Our estimate of the mass of a winged balloon guidance system, consisting of a wing, its winch and control system at the gondola, and a tether is between 15 and 150 kg, depending on the size of the balloon to be guided, the desired performance of the system, and the level of lightweight material technology incorporated into the design. The current prototype guidance system is projected

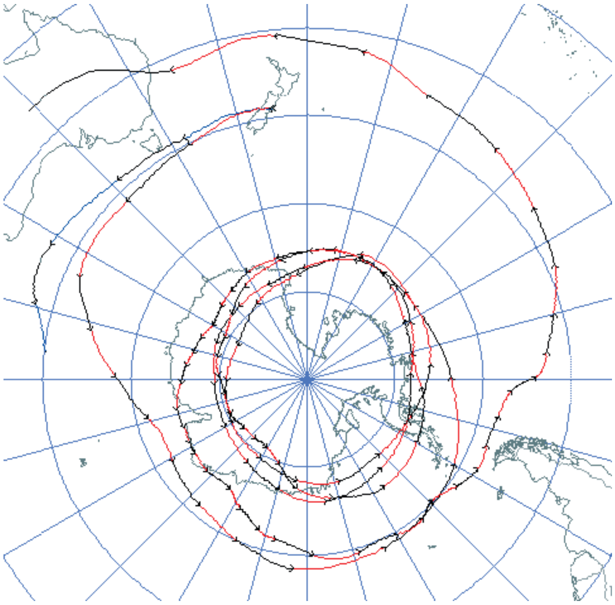

Fig. 6. A 105-day flight simulation of the performance of a winged balloon guidance system to modestly adjust the flight path of a large stratospheric balloon in historical winds. The alternating red and black line segments represent 1-day increments. In this example the balloon is launched from Christchurch, New Zealand, and is directed southward by the guidance system to go to −70° latitude, where it performs rough latitude control (±2°) for about 65 days, after which it is directed northward for an eventual landing near Alice Springs, Australia. The short trajectory path shown to the right after launch is the path the balloon would have initially followed without control. Key simulation assumptions were launch on 15 Nov 1998, a 100-m-diameter balloon at 35-km altitude, a 5-m wing at 20-km altitude, and a very simple guidance algorithm (Nock et al. 2007). This simulation used a high-fidelity aerodynamic model of the winged guidance system.

to weigh 155 kg; however, it was not designed to be lightweight. The tether, a key element of the system, could be a braided cable nominally made from polybenzoxazole (PBO) fiber, of which two 15-kg, 15-km-long examples have been built, with a breaking strength of about 1800 N. The predominant force on the tether will be the weight of the wing, on the order of 1000 N for the heavy prototype, as compared to the horizontal and vertical components of the aerodynamic forces on the order of 100 and 10 N, respectively. We estimate that the mass of the operational tether, including its UV/light protection, will be about 1–2 kg km^{-1} of tether length for a 90-kg wing (the projected mass of our prototype), depending on the required safety factor on the tether. A tether designed to support both a wing and a tether crawler will be somewhat heavier.

Constellation topology control. For balloon constellations, sophisticated guidance and coordination algorithms are needed to control individual balloons to maintain the desired topology of the constellation. Control laws based on artificial potentials (AP) and weak stability boundary theory are attractive options for providing coordinated control of the distributed balloons (Heun et al. 2003). The use of artificial potentials is inspired by the observations and models of groups in nature (e.g., flocks of birds and schools of fish) that make use of a distributed control architecture. Individuals respond to their sensed environment but are constrained by the behavior of their neighbors. For artificial potential control algorithms, the following elements are basic to maintaining a group structure: 1) attraction to distant neighbors up to a maximum distance, 2) repulsion from neighbors that are too close, and 3) alignment or velocity matching with neighbors. To apply the AP theory to StratoSat constellations, local StratoSat traffic rules are encoded by means of (local) artificial potentials in control algorithms that define artificial interaction forces between nearby StratoSats. Each of these potentials is a function of the relative distance between a pair of neighbors. Using such a method, the control forces drive the StratoSats to the minimum of the total potential, which, because of the way the potentials have been defined, corresponds to the desired constellation topology. Thus, the artificial potential approach defines control actions for individual members of a constellation, leading to higher functionality at the group level. Intelligent, shape-preserving group behavior emerges from decentralized, individual-level rules. Figure 2 illustrates the global distribution of a constellation of StratoSats that can be achieved with modest flight path guidance and using artificial potential control to establish and maintain a uniform global distribution. Although much work needs to be done to extend this control technology, the work already accomplished (Heun et al. 2003) gives high confidence that small constellations can be controlled well enough to carry out the important Earth science observations discussed earlier.

FIG. 7. A photograph from a flight test showing a 1/4-scale model suspended from a tethered blimp in windy conditions. Scale model tests were very successful in demonstrating performance and stability predictions in the Reynolds number regime in which the full-scale system will operate. A combined-system lift coefficient of 1.2 was measured at Reynolds numbers of about 45,000. For reference, the main wingspan of the model is 1.41 m, its chord is 0.308 m, and its mass is 3.4 kg.

In situ measurements. The in situ measuring capabilities of StratoSats could be enhanced and extended with lightweight meteorological and flux divergence dropsondes and innovative "crawlers" that would move up and down the tether carrying a suite of science sensors. The National Center for Atmospheric Research (NCAR)-designed aircraft dropsondes currently in use operationally have a mass of approximately 400 g with a smaller, 170-g sonde developed for deployment from stratospheric balloons. NCAR has already produced a 50-dropsonde canister capable of sonde deployments either at preset times or on command. The system was deployed on a small (905 cubic meter) French Space Agency super-pressure balloon for research purposes during the African Monsoon Multidisciplinary Analysis Project (D. Parsons 2007, personal communication). A canister holding 4000 dropsondes would be well within the lifting capability of a StratoSat.

Current aircraft GPS dropsondes are produced in small numbers for research purposes. A larger production rate (on the order of 40,000 per year) could lower the costs to somewhere between the current amount and the costs of operational radiosondes. Advances in miniaturization and carbon composite materials may further lower costs per sounding and allow additional measurements, such as radiative flux (using new miniaturized gyroscopes) and cloud liquid/ice content.

Tether crawler systems could carry much heavier, more capable payloads than dropsondes (~45-kg payload for one studied concept). The crawler would descend in about 1 h at about 5 m s^{-1} under the force of gravity limited by controlled friction. The return trip up the tether would be powered by solar panels attached to the crawler. Data would be transmitted by radio from the crawler directly to the StratoSat gondola.

Flight termination and safety systems. When a StratoSat flight needs to be terminated, it is highly desirable to recover the science payload on land. It is also mandatory that the parts returning to Earth fall away from populated areas. Fortunately, development of GPS-guided parafoil and parachute technology has been underway for more than 10 years, starting with the French Orion system (Vargas and Evrard 2000) and, more recently, in developments in support of national defense applications (Benny et al. 2007). In 1998 and 1999, the French Space Agency conducted three successful flight tests of a balloon payload termination and recovery system that was designed to be deployed from a balloon at 33-km altitude and, by means of GPS-guided parafoils, could land payloads at airfields up to 20 km away from the termination point.

SUMMARY. At present, no investment is being made in developing very long-life stratospheric balloon technology primarily for Earth science applications. The current investments are focused on multiton astrophysical payloads that look upward into space and that usually care little about their geographic location except when they desire a view of either the northern or southern celestial sky. Earth science balloon technology requires a different development path because trajectory guidance is essential and, because payloads are lighter, balloons can be made much smaller. Nevertheless, most technology could be adapted from the astrophysical balloon technology path and thus comes heavily leveraged. The existing balloon launch facilities in Texas, New Mexico, Alaska, Sweden, Australia, and Antarctica could also be used. If the necessary steps to realize the promise of very long-life stratospheric platforms for Earth science are taken, constellations of StratoSats could work in collaboration with other elements of the Earth observation "sensor web" like UAVs and satellites to transform our understanding of the Earth and its atmosphere. The cost of a constellation of 100 StratoSats is less than a cost of a single satellite because they are inherently much less costly and because, unlike with satellites, economies of scale further drive down the price. In addition, StratoSats could allow a more rapid and flexible iteration cycle in instrumentation and observing strategy than is possible with satellites. Once their potential in this regard begins to be realized, we expect that students and professors will find them to be very attractive platforms for their own measurements as well as for educational purposes. Indeed, in the astrophysical community the balloon program is a training ground for students who eventually go on to propose and win satellite investigations.

StratoSats could make important contributions in four scientific areas today. First, they could validate climatically crucial Earth radiation energy budget retrievals made using satellites and help to eliminate the current diurnal and sun-angle biases; constellations could help reveal the dynamic quality of radiative fluxes in short-term events such as dust outbreaks. Second, StratoSats could study stratospheric and upper-tropospheric chemistry, especially water vapor, which exerts a profound feedback effect on climate, and measure trace gas profiles for unprecedented durations and for regions above 20 km rarely sampled in situ. Third, they could map the Earth's crustal magnetic field at never-before-achieved spatial scales, producing a revolutionary map of the magnetic Earth that could lead to new understandings of the Earth's crust. Finally, they could patrol the tropical and midlatitude atmosphere to provide measurements that could improve the predictions of the paths and intensities of storms and, by dropping dropsondes on command, provide adaptive measurements to improve the predictability of weather. In summary, the development of StratoSat constellations will enable new science and new observational techniques that will help us to advance Earth science in many ways that can be foreseen today, and, as is common with new platforms, other ways that are as yet only dimly perceived are certain to emerge.

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