GLOBAL CONSTELLATIONS OF STRATOSPHERIC SATELLITES

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ABSTRACT

Global Aerospace Corporation (GAC) is studying a revolutionary concept of global and regional constellations of very long life, stratospheric superpressure balloons which can address major scientific questions and expand scientific knowledge of the Earth system. At a speed of 30 m/s, typical of the zonal stratospheric winds at 35-km altitude, a long life balloon can "orbit" the Earth along a latitude band like a space satellite every 10-20 days, but at a much lower altitude. Regional and global constellations of hundreds of stratospheric satellites can address major scientific questions relating to Earth science by measuring stratospheric gases, collecting data on atmospheric circulation, observing the Earth's surface, and detecting and monitoring environmental hazards. Such a system could augment and complement satellite measurements.

1 INTRODUCTION

GAC is studying a new concept of low-cost stratospheric satellites, called StratoSat™ platforms based on advancements in NASA's Ultra Long Duration Balloon (ULDB) technology currently under development. StratoSat™ networks and constellations can address issues of high interest to the Earth science community including global change, especially tropical circulation and radiation balance; global and polar ozone; hurricane forecasting and tracking; global circulation; and global ocean productivity. Regional and global constellations of stratospheric superpressure balloons can measure stratospheric gases, collect data on atmospheric circulation, observe the Earth's surface, and detect and monitor weather and environmental hazards. Fig. 1 illustrates the concept and the StratoSat™ system features.

2 SUPERPRESSURE BALLOONS

NASA is currently developing a new platform called Ultra Long Duration Balloon (ULDB) that will fly up to 1000 kg science payloads above >99% of the Earth's atmosphere for at least 100 days. ULDB is a fixed volume balloon with an important difference; the envelope is strong enough to prevent bursting when the balloon reaches its volumetric capacity. Upon reaching this point the pressure inside the balloon envelope is slightly higher than outside (superpressurized) and the envelope becomes stressed. Superpressure balloons fly at a nearly constant altitude where the average density of the floating system equals the density of the air. This class of stratospheric platforms will provide a major leap forward in return on investment of scientific time and money. A number of technology efforts relevant to stratospheric balloon constellations are currently ongoing under the NASA ULDB Project including balloon system design, trajectory simulation and prediction and balloon trajectory control systems [3]. StratoSats™ platform technology will be based upon an advancement of ULDB technology. Some of these advancements include lower mass, stronger envelope materials, lightweight UV protection, integrated envelope and solar array technology, and improved manufacturing quality to minimize leakage.

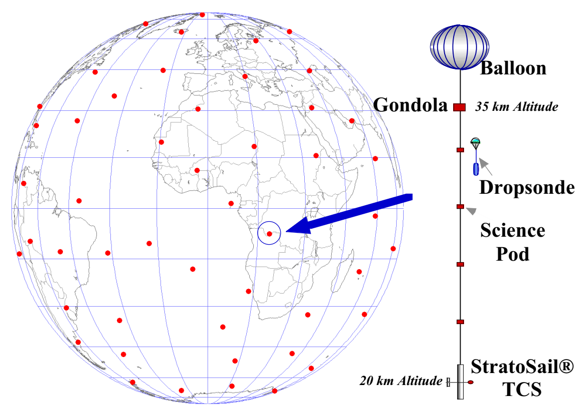

Fig. 1. Global Constellation Concept and StratoSat™ Platform Features

3 EARTH OBSERVATIONS AND SCIENCE

As with space satellites, StratoSat™ systems will be global in nature and essentially orbit the Earth. As with balloons, StratoSat™ platforms will fly much lower and slower than space satellites, enabling *in situ* measurements not possible from space satellites, and improving surface and atmospheric remote sensing performance. The following list is an example of Earth observation and science missions for global and regional constellations of stratospheric platforms that address major Earth science issues. Each of these examples is discussed in more detail in [1,2].

A. Global Change Studies
   1. Global Circulation in the Tropics
   2. Radiative Studies in the Tropics

3. Global Radiation Balance

B. Ozone Studies
   1. Mid-latitude Ozone Loss
   2. Polar Ozone Loss
   3. Global Distribution of Ozone

C. Weather and Adaptive Sampling
   1. Hurricane Forecasting and Tracking
   2. Tropospheric Winds
   3. Forecasting Weather from Remote Areas

D. Tropical Rainfall

E. Global Circulation and the Age of Air

F. Global Ocean Productivity

G. Environmental Monitoring

H. Hazard Detection and Monitoring

The development of stratospheric constellations will enable new science and Earth observation techniques. Constellations can help to better understand Global Change, the extent to which mankind can influence this change, and what to do about such change. A few of these applications are discussed in the next sections.

3.1.1 Global Earth Radiation Budget (ERB)

An application of StratoSat™ platforms constellations is in a dense global network carrying calibrated radiometers. In such a network, radiative flux is measured directly at 35 km. This altitude is the commonly accepted top-of-the-atmosphere (TOA) to which satellite ERB products are extrapolated. With these in-situ measurements, no extrapolation is required from 800 km down to 35 km. At this low altitude, high spatial resolution measurements are possible, no angular modeling is needed and 90% of the irradiance is within a 200-km footprint (70° FOV). Since complete diurnal coverage is possible, diurnal modeling, the leading source of uncertainty in daily and monthly regional flux averages, is not required. Global synoptic coverage, thus achievable, enables the actual dynamics of ERB to be seen (including horizontal fluxes); never before possible.

3.1.2 Hurricane Forecasting and Tracking

Disruption of life and devastation of property typically occur along the path of a hurricane. The prediction of the paths of hurricanes has improved over that last 30 years, primarily due to the availability of space satellite data and fast computers. Even so, 72 hours before landfall the predictions are still in error on the average by 200 miles [4]. In addition, when a hurricane is forecast to hit a coast on a near normal trajectory, up to 300 miles of coast are placed under a hurricane warning, which is about 4 times the zone that will actually be seriously effected. The financial impact of hurricane warnings is the cost of evacuation of coastal areas and the subsequent economic disruption that follows. Depending on the economic sectors along a stretch of coast, the full cost has been estimated between $1-50M per mile evacuated [5]. Assuming $1M per mile for evacuation costs, if the overwarning ratio could be cut in half, reducing the coast evacuation to 150 miles, a savings of about $150 M would be realized for just one hurricane landfall! We have estimated the cost of emplacement of a 100-balloon network at only $39 M [6]. The economics indicate that it may be useful to examine further the cost and benefits of a regional balloon constellation that is focused on improving hurricane tracking and prediction.

The winds in the vicinity of the hurricane are important for predicting where the hurricane is going. The winds inside the hurricane are important to estimate the eventual intensity of the hurricane. Both wind measurements are needed. Currently, space satellites provide low resolution atmospheric data, buoys provide surface wind, pressure, air and ocean temperature, and manned aircraft fly into the storm to supplement the wind, pressure and temperature data around the storm. While this network of information has continued to improve hurricane forecasting, more high quality, high resolution in situ data is needed.

A constellation of StratoSat™ systems could be used to address this problem. Orbiting in the tropics over the Atlantic (and Pacific) they could carry dropsondes to measure wind, temperature and pressure in he vicinity of the hurricane. This added information would provide significantly increased data for the models. With a projected sonde mass in ten years of 10 to 25 grams, each balloon payload could have more than 1000 sondes for this experiment, which provide profiles from balloon altitude to the surface. In addition to the dropsondes, a high-resolution Precipitation Radar may be an important instrument on such a payload due to its ability to provide additional data on storm intensity. See the following URL for example hurricane intercept and tracking simulations http://www.gaerospace.com/publicPages/projectPages/StratCon/conMgtSims/index.html.

3.1.3 Environmental Monitoring

Because airborne products of industry and transportation diffuse and flow beyond political boundaries, pollution can no longer be viewed as a regional problem but a world problem. The mitigation of pollution will demand global political solutions that will require global monitoring and controls. Products of pollution are very difficult to detect from space, especially with sufficient accuracy and spatial resolution, at the present time and for the foreseeable future. A potential role for global stratospheric platforms is the global measurement and monitoring of the worldwide pollution and other environmental problems. In addition, StratoSats could be an important component of a monitoring system that will complement satellite instruments. One potential method of making these measurements is by the use of LIDAR systems from a

StratoSat. The quality of active remote sensing measurements (e.g. LIDAR) of rare species in the atmosphere is a function of the r-squared law of the diminution of signal. Assuming the same signal strength at a 15-km altitude atmospheric target, a StratoSat platform at 35-km altitude will see about a 1200-times higher returned signal as would a satellite observe from a 700 km orbit. Furthermore, the integration time is longer from a slowly moving stratospheric platform compared to a satellite.

3.1.4 Tropospheric Winds

Several researchers are interested in the possibility of measuring tropospheric winds using Lidar on a balloon platform in the stratosphere. Some differences between a satellite and balloon Lidar have been examined. Since the StratoSat operates lower there is a gain in SNR that can be translated to lower operating power and/or higher sensitivity and/or reduced telescope aperture and thus size. For the same focal length, the footprint of the Lidar is smaller, meaning higher spatial resolution is possible. For a fully optimized experiment one expects to achieve significant improvements in spatial (2-4 km) and vertical resolution (100-200 m) and wind speed accuracy (<1 m/s). Since a global network of StratoSat platforms will operate at a wide variety of local times, good diurnal coverage is expected as contrasted with a Sun synchronous satellite that only observes two times of day.

4 INTERNATIONAL OVERFLIGHT

A number of pathways to global overflight of balloon constellations exist including (1) the exercise of the principle of free flight in the upper stratosphere, (2) incorporation of constellation systems into the Basic Systems framework of the World Meteorological Organization (WMO), (3) expansion of the Treaty on Open Skies (TOS), or (4) a new treaty based on the free use of the stratosphere for scientific purposes or the need to monitor the troposphere for worldwide pollution control compliance.

4.1 Free Flight in Upper Stratosphere

A rationale for free flight of the stratosphere is that (1) sufficient ambiguity exists as to the limits of airspace and hence of a State's sovereignty, (2) no treaty or agreement exists that unambiguously regulates or controls flight above 18 km altitude, and (3) as with outer space, few States, if any, have special national interests in the upper stratosphere or the means to exercise control over activities within the upper stratosphere. The lack of clear definition and demarcation of airspace provides an opportunity for the free use of the upper stratosphere provided this use is in a manner that satisfies existing rules of law and such operation does not compromise national interests of the over flown State. Operating in the stratosphere under a principle of free overflight would provide an opportunity to deal with each issue as it arises, in a similar fashion as navigation on the high seas and outer space has developed. In this way, a common law of the upper stratosphere would be allowed to develop.

4.2 World Meteorological Organization Cooperation

One of the WMO teams of interest to future global constellations is Open Program Area Group (OPAG) on Integrated Observing Systems (IOS). The OPAG on IOS is divided into implementation and coordination, observational data requirements, satellite, and automatic station teams. Each of these teams meets about every two years to formulate the WMO program in the IOS area. New ideas, such as global constellations of balloon platforms, are formulated, discussed and analyzed at the lowest levels before they move upward through the WMO. Given past examples, it can take a decade or more after they are presented for new observing techniques to be accepted by the WMO. Once accepted, however, all member States support the new technique and provide infrastructure to implement, e.g. satellites, radiosondes, buoys, etc. If constellations of stratospheric balloon platforms were recognized as a cost effective means of satisfying the CBS requirements and as a result accepted by the WMO Council, such constellations would not require international treaties. All member states would be offered the opportunity of contributing balloons systems to the global network.

4.3 Expand Treaty on Open Skies

On March 24, 1992, 25 nations signed the Treaty on Open Skies (TOS) in Helsinki, Finland [7]. When fully implemented, the treaty will establish a regime of unarmed military observation flights over the entire territory of its signatory nations. The TOS was originally negotiated between members of NATO and the former Warsaw Pact as a confidence building measure in arms control. The Treaty on Open Skies is a positive step toward building confidence and security in the arms control and verification process ongoing between signatory nations. The TOS gives one hope that in the future global stratospheric constellations of unarmed scientific platforms would be allowed to operate. The TOS is a positive step toward building confidence and security in the arms control and verification process ongoing between signatory nations. The TOS provides hope that in the future global stratospheric constellations of scientific platforms would be allowed to operate. In fact, the preamble leaves open this possibility when it envisions, ". . .*the possible extension of the Open Skies regime into additional fields, such as the protection of the environment*."

4.4 Seek New Treaties

There is interest in the international scientific ballooning community to establish new international agreements for the free use of the stratosphere by scientific balloon systems. This interest is independent of Global Aerospace Corporation's interest in the international overflight of constellations of balloons.

At the 33rd COSPAR Scientific Assembly in Warsaw, Poland in 2000, the Scientific Balloon Panel formulated a resolution to the COSPAR Executive Council requesting a task group be formed to study and report to the bureau on the technical aspects of overflight of scientific balloons (including altitudes, balloon sizes and payload masses, characteristics and features of payloads, and safety requirements) and possible international actions to enable the geographically-unrestrained and the peaceful free flight of such apparatus over all countries. This resolution was accepted as COSPAR Internal Decision No. 1/2000 [8]. It is hoped that this initiative will eventually result in a new agreement that perhaps could recognize the stratosphere as a special zone for scientific balloon and lighter-than-air (LTA) craft where they could fly without overflight constraints provided they meet certain technical, legal and oversight requirements. Possible requirements are listed below:

- Airworthiness certificates from appropriate organization, perhaps ICAO, indicating the craft meets equipment and safety requirements
- A means of identification
- Evidence of liability insurance
- Payloads must not compromise any State's national security
- Launch and payload oversight
- Any nation free to operate stratospheric platforms if they meet all requirements

Finally, new diplomatic initiatives regarding the protection of the worldwide environment could instigate new international treaties for monitoring pollution. Such monitoring may require global constellations of stratospheric platforms, such as balloons, to make the measurements possible due to their proximity to the troposphere.

5 STRATOSPHERIC CONSTELLATION GEOMETRY MANAGEMENT

It would be very nice to have a free balloon that could remain stationary over a geographic zone (i.e. stationkeeping) in order to continuously observe a fixed location. However, balloons at any altitude are subject to the circulation of the atmosphere. Generally, the atmospheric circulation in the stratosphere is zonal in nature; moving from east to west or west to east depending upon season of the year. There is also a highly variable but small component of stratospheric circulation that is meridional in nature, exhibiting a long-term average drift away from the equator toward the poles [9]. If a constellation of constant altitude (35 km) balloons were to be uniformly spaced over the globe, this average poleward drift would eventually concentrate the balloons in the vicinity of the poles.

Balloons and other lighter-than-air systems, which can stationkeep over a geographic point by thrusting against the wind, have been the subjects of several studies over the years [10,11]. Stationkeeping over a single point is extremely energy intensive and requires power and propulsion system mass to be carried to fight the winds. The concept described herein allows a near-uniform constellation of many balloons to constantly float in orbit around the Earth carrying out measurements. This network achieves virtual stationkeeping. When one balloon passes over the horizon and leaves a zone, another enters the zone and replaces it.

By continuously nudging a balloon in the latitudinal direction as the balloon repeatedly circles the Earth, the meridional drift can be counteracted, thereby preserving the structure of the constellation. Global Aerospace Corporation is currently developing, under NASA funding, a system for stratospheric balloon trajectory control [12]. Such a system, when combined with accurate balloon trajectory simulation and prediction capability, can provide the level of trajectory control required for maintaining a uniform configuration of a StratoSat™ platform constellation.

6 STRATOSAT™ SYSTEM DESCRIPTION

The mass estimate of an example StratoSat™ system capable of a 35-km float altitude is summarized in the following Table 1. The science payload was derived from a Global Circulation in the Tropics science objective.

Table 1 Example StratoSat Mass Summary

Subsystem	Mass, kg
Balloon	252.0
Helium	87.4
Gondola	63.1
Trajectory Control	80.7
Science	77.2
Total	560.4

6.1 Science

In general, science experiments and instruments can be in the gondola, along the TCS tether, on the TCS and within small packages, or dropsondes, dropped from the gondola to the surface. An example Global Circulation in the Tropics payload was selected in order to drive the StratoSat™ gondola design shown later .

6.2 Balloon

The StratoSat™ platform design assumes the so-called pumpkin balloon design of the NASA ULDB Project. Fig. 2 is a photograph of a ULDB scale-model, pumpkin balloon test. The balloon subsystem provides the buoyancy for the StratoSat. The StratoSat balloon envelope is about 60 m in diameter and about 35 m high. The shell is comprised of 140 gores or sectors of 15-g/m^2 areal density film similar to the co-extruded composite under study for the ULDB Project, only thinner. The film material would be protected from UV damage either with UV inhibitors within the film or a thin coating on the outside. Each gore would be about 1.34 m wide and about 77 meters long, and attached to its neighbor by means of a heat sealed seam. At each seam is a load-bearing tendon made from the high strength material Zylon®. The reefing sleeve, fittings and flight train systems are patterned after the ULDB systems. Additional balloon subsystem hardware is required to monitor balloon health (pressure, temperatures, UV damage, and envelope stress), to valve buoyant gas and to replenish buoyant gas if necessary. Expected loss of helium due to diffusion through the balloon envelope is only about 1.5 g/day at operational altitude, superpressure and temperature. At this rate there will be a loss of 2.7 kg of helium over the 5–year nominal StratoSat lifetime. A simple buoyancy gas make-up system is employed.

Fig. 2. ULDB Scale model Pumpkin Balloon Test (courtesy NASA Balloon Programs Office)

6.3 Power

The power subsystem consists of power generation (solar array), power management and distribution, and energy storage components. For the purposes of this reference design we have assumed the integration of thin-film, 10% efficient, amorphous-Silicon solar array into the balloon envelope within the center of the balloon gores. The total area of array required is only 90 m^2 with a 5 kW power requirement. The batteries for StratoSat have been assumed to be lithium-ion polymer at an energy density of 200 Wh/kg.

6.4 Trajectory Control System (TCS)

The StratoSail® TCS produces the force to move the balloon platform in a desired direction. Suspending an aerodynamic surface, or wing, several kilometers below the balloon, generates this force taking advantage of the high relative winds between widely separated altitudes. In addition, the TCS provides a scientific platform at the level of the suspended wing and at places all along the tether between the wing and the balloon. One possible TCS design is shown in fig. 3.

The TCS includes the wing assembly, the tether, a winch system, and interface electronics and radios to communicate with the gondola. While the TWA tether is extending, several small science pods are attached to the tether at intervals of a few kilometers. This provides the ability to take simultaneous measurements at several different altitudes.

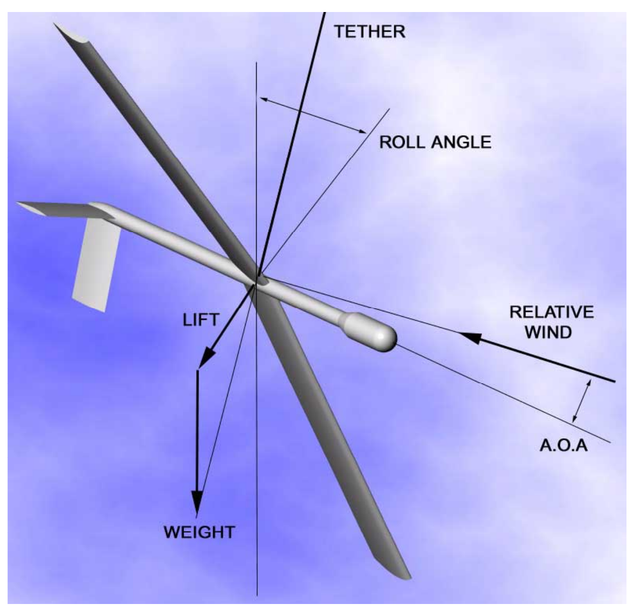

Fig. 3. Advanced TCS Design Concept

6.5 Gondola

The gondola contains the guidance and control electronics, radios, gondola-mounted science sensor electronics, and many TCS-related subsystems. The guidance and control subsystem provides onboard navigation and orientation knowledge information, and it provides subsystem and science articulation functions. The guidance and control subsystem consists of ambient atmospheric, celestial, acceleration, rotation rate and GPS sensors for determining the state of the StratoSat and the environment in which it is floating.

The communications subsystem includes hardware to communicate with the operation center, communications satellites, and aviation authorities. This subsystem consists of transmitters and receivers, signal conditioning and decoding hardware, antennas and radar reflective components. Two LEO satellite communications links are assumed; a high rate, 6 Mb/s link and a 2.4 kb/s link for low-rate science data. Figure 4 illustrates the gondola design for the example StratoSat.

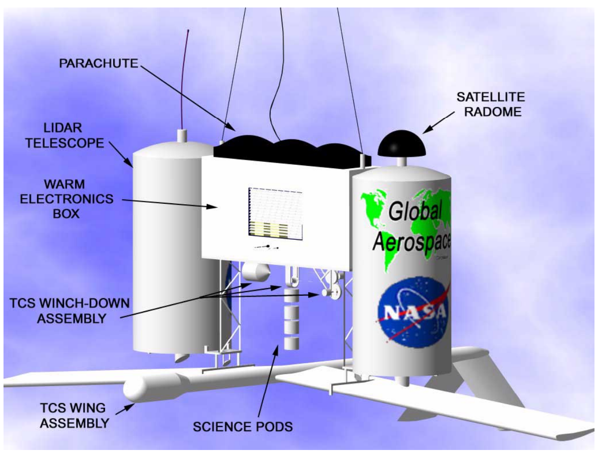

Fig. 4. Example StratoSat Gondola Design

7 SUMMARY

A revolutionary concept has been described for a global constellation of hundreds of controlled stratospheric satellites that can cost effectively address major scientific questions relating to Earth science.

8 ACKNOWLEDGMENTS

We would like to acknowledge the support of the NASA Institute for Advanced Concepts through their Universities Space Research Association Grant Nos. 07600-25 and 07600-58. In addition, we acknowledge the efforts of Dr. Elliot Weinstock of Harvard University and Mike Smith of Raven Industries, who participated in the early study.

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