GLOBAL STRATOSPHERIC BALLOON CONSTELLATIONS

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ABSTRACT

A revolutionary concept is discussed for a global constellation and network of hundreds of stratospheric superpressure balloons that can address major scientific questions relating to Earth science. Global Aerospace Corporation is proposing this role for a new generation of stratospheric platform based on advanced balloon technology, called the *StratoSat*. StratoSat 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. StratoSat constellations operating at a 35-km altitude and for 5 to 10 years in duration could augment and complement satellite measurements and possibly replace satellites for making some environmental measurements. The keys to this new concept are (a) affordable, long-duration balloon systems, (b) balloon trajectory control capability, and (c) a global communications infrastructure. Technology for these very long-duration and guided stratospheric balloons is summarized, constellation geometry management is discussed, international overflight issues are explored, and the StratoSat system design is described.

INTRODUCTION

Regional and global constellations of hundreds of stratospheric superpressure balloons 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 and possibly replace satellites for making some environmental measurements. Figure 1 illustrates the concept and the StratoSat features.

A Changing Paradigm

In the satellite era, there has been a shift away from making conventional *in situ* measurements of the global environment to remote sensing from Earth orbiting spacecraft. The reasons for this shift have been global accessibility afforded by satellites; high cost of conventional *in situ* measurement operations, due to workforce (particularly in remote areas) and hardware cost issues; and appropriate national priorities that emphasize the application of high technology space systems as the solution to global science measurements. After forty years, there may be some reason to challenge this remote sensing paradigm with a new *in situ* strategy. In combination, (a) the advance of electronics, communications and balloon technologies, (b) the inherent difficulty of making some remote measurements from satellites, and (c) the interest in simultaneous global measurements, argue for a reevaluation of the current reliance on satellites for many global environmental measurements.

In addition, total system cost for a constellation of stratospheric superpressure balloons may be competitive with or lower than comparable spacecraft systems due to the inherent high cost of spacecraft and launch vehicles.

Current Earth Observation Vantage Points

Today the Earth is observed from a number of vantage points including the ground; polar orbiting and geosynchronous Earth orbit (GEO) satellites; research aircraft; balloon-borne radiosondes and aircraft-released dropsondes; and conventional short-duration, high-altitude research balloons.

Satellites

Generally, satellites that observe the Earth are in polar or geosynchronous orbits. Satellites in polar orbits have wide access to latitudes. However, the high inclination and altitude of these satellites have an adverse implication to satellite remote sensing. The high



Fig. 1. Global Constellation Concept and StratoSat Features

altitudes mean large distances between sensors and targets. The high altitudes mean large distances between sensors and targets.

Observations of the Earth from GEO satellites have typically been restricted to kilometer-scale visible and IR imaging for meteorology purposes. In addition, because of the curvature of the Earth, GEO satellites cannot make useful surface remote sensing observations above about 70 degrees latitude. Because of the large investment in simply getting into space, project managers invest a lot of money into insuring their spacecraft and instruments will meet the reliability and space environmental requirements.

Aircraft

A variety of aircraft and sensor systems are dedicated to the support of remote and in situ sensing atmospheric, land, and ocean processes research. For high-altitude research NASA uses a ER-2 and a WB-57. These aircraft can perform experiments between 12-20 km; cruise at about 200 m/s and have ranges between 5000-6000 km. The per-hour areal operations costs are relatively high as compared to global satellite systems due to the high level of expertise required of personnel and the high level of safety required. Some weaknesses of aircraft for high-altitude Earth science research include: (a) high air-relative velocity, which complicates in situ chemistry measurements, (b) limited range, (c) high operations costs, (d) limited flight duration, (e) limited number of aircraft, and (f) limited altitude

NASA's Unmanned Aerial Vehicle (UAV) research continues to pursue long-duration, highaltitude (30.5 km [100,000 ft]) flight goals that enable important Earth science observations. However, the realities of UAV performance for high altitude research have yet to meet their promise. Even if this vehicle class meets its goals, there will still be the issues of the limited payload capability and high development, production and operations costs; in addition to safety. A recent estimate of the cost of a NASA solar-powered UAV are \$3-5M each with a development price tag of over \$300M (Colker, 2000). Current estimates of operations costs for reconnaissance and strike UAVs indicate that they approach the costs of crewed aircraft (Wall, 2000).

Radiosondes and Dropsondes

The role of radiosondes, small balloons carrying operational instruments that take data on ascent until the balloons burst, is important to Earth science measurements, and their use is wide-spread, especially for meteorology. Radiosondes, and their counter part, dropsondes, which are released from aircraft at high altitude, now carry a variety of *in situ* instruments that go beyond the traditional meteorology measurements. Instrumentation can include chemical gas sensors plus Global Positioning System (GPS) receivers to measure wind profiles. The high cost of such measurements in remote areas and the difficulty to achieve very high altitudes, e.g. 20-35 km, currently limit radiosonde usage.

Conventional Balloons

Conventional zero-pressure stratospheric balloon platforms have and will continue to contribute to Earth science research by providing complementary *in situ* and remote sensing measurements to satellites. They can provide "ground truth" in regions of the atmosphere of interest to satellite experimenters. Scientific balloons carry research instruments that take data on ascent, float and descent and weigh hundreds to thousands of kilograms. Though they have limited lifetime (2–14 days), they continue to provide calibration and validation data for satellite data sets, as well as high-resolution measurements not achievable by satellite measurements.

The strengths of conventional balloons include the ability to (a) cover stratosphere and troposphere from 40 to 10 km, [much of this] above aircraft [altitudes], (b) provide simultaneous measurement of multiple species, (c) provide high-resolution vertical profiling across large pressure range, and (d) simulate remote sensing footprint of limb sounding satellites. Weaknesses of conventional balloons are that they (a) provide infrequent measurements, except for small balloons or in intensive mode, (b) give only vertical profiles - no probing of horizontal gradients, and (c) are sometimes questionably cost effective for science and validation gained [due to limited mission duration], (Brune, 1999).

Ultra Long Duration Balloon (ULDB)

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 one 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. All the strengths listed in the section above are valid for the ULDB-class of very long duration stratospheric platforms and most of the weaknesses tabulated above for conventional balloons are made moot by ULDB. The ULDB 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.

POTENTIAL CONTRIBUTIONS OF STRATO-SPHERIC BALLOON CONSTELLATIONS

As with satellites, StratoSats will be global in nature and essentially orbit the Earth. As with balloons, StratoSats will fly much lower and slower than satellites, enabling *in situ* measurements not possible from satellites, and improving surface and atmospheric remote sensing performance.

Earth Science

The following list is an example of Earth 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 Weinstock and Nock (1999).

- a. Global Change Studies
 - Water Vapor & Global Circulation in Tropics
 - Radiative Studies in the Tropics
 - Global Radiation Balance
- b. Ozone Studies
 - Mid-latitude Ozone Loss
 - Polar Ozone Loss
 - Global Distribution of Ozone
- c. Hurricane Forecasting and Tracking
- d. Global Circulation and the Age of Air
- e. Global Ocean Productivity

The development of stratospheric constellations will enable new science and Earth observation techniques that themselves will lead to a better world. Global constellations can help to better understand Global Change, the extent to which mankind can influence this change, and what to do about such change.

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.

Weather Forecasting

Better forecasting of weather phenomena, especially hurricanes, will be available with global constellations that can make *in situ* measurements from 35 km to the surface, especially in remote areas. Improved forecasts will help to limit future catastrophic damage and injury because more accurate predictions will be available earlier.

INTERNATIONAL OVERFLIGHT ISSUES

Today, permission to fly scientific research platforms, balloons and aircraft, over some nations is difficult to impossible to obtain. Often, intensive international diplomacy is required to allow overflight. In addition, the changing international political climate can heavily influence the authorization of overflight.

It is very clear that for global stratospheric balloon constellations to be possible, international agreements are needed. National sovereignty usually applies to airspace but not outer space. At this time there is no established definition of the height at which airspace ends and outer space begins, though it has been suggested that the end of airspace and the beginning of outer space be located between the upper flight height of aircraft and the lower orbit of spacecraft (Kish, 1973). This ambiguity raises the opportunity for future international agreements to address the peaceful and safe scientific uses of the region between airspace and outer space.

On March 24, 1992, 25 nations signed the Treaty on Open Skies (TOS) in Helsinki, Finland. 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 security measure in arms control. The TOS gives hope that global stratospheric constellations of scientific platforms would be allowed to operate in the future. The preamble to the TOS 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."

Another potential framework for establishing international agreements for global constellations of Earth science balloons is through the aegis of the World Meteorology Organization (WMO). If global constellations of balloons where part of the WMO worldwide network of meteorology and environmental measurements, all member nations would allow overflight. The path to WMO approval and incorporation of global balloon constellations is challenging; however, the WMO is a proven path that could insure worldwide acceptance.

STRATOSPHERIC CONSTELLATION GEOMETRY MANAGEMENT

It would be very nice to have a free balloon which 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 longterm average drift away from the equator toward the poles (Eluszkiewicz, et. al., 1996). 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 (Vorachek, 1970; Beemer, 1975 and others). Stationkeeping over a solitary point is extremely energy intensive and requires power and propulsion system mass to be carried to fight the winds. The concept proposed herein allows a near-uniform constellation of many balloons to constantly float 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 (Aaron, 1999). 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 balloon constellation.

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 the Water Vapor and Global Circulation in the Tropics science mission.

| Table T Example Sualosat Mass Summary | |
|---------------------------------------|----------|
| Subsystem | Mass, kg |
| Balloon | 252.0 |
| Helium | 87.4 |
| Gondola | 63.1 |
| Trajectory Control | 80.7 |
| Science | 77.2 |
| Total | 560.4 |
| | |

Table 1 Example Strate Set Mass Symmetry

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 payload was selected in order to drive the StratoSat system design. The payload described below addresses the science objective of the understanding the water vapor and global circulation in the tropics.

At the gondola are: (a) ozone LIDAR (ozone profiles to ground), (b) water vapor LIDAR (water vapor profiles down to mid troposphere), (c) water vapor and ozone infrared absorption instruments, (d) cavity ringdown-laser absorption spectroscopy for CO_2 , and temperature measurements.

Along the tether (2, 4, and 6 and 10 kilometers above the StratoSail® TCS) are water vapor and ozone infrared absorption instruments and temperature measurements.

At the StratoSail® TCS (at 20-km altitude) are a microwave temperature profiler at bottom of the tether, which measures temperature to about 6 km below the instrument, water vapor and ozone infrared absorption instruments and temperature measurements.

This payload would also provide a continuous picture of water vapor entering the stratosphere. It would address issues involving our understanding of how much water enters the stratosphere on an annual basis and provide a basis for our understanding trends or variability in stratospheric water which have been observed by satellites and sonde data.

Balloon

The StratoSat design assumes the so-called pumpkin balloon design of the NASA ULDB Project. Figure 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/m² 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 loadbearing 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 makeup system is employed.



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

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 thinfilm, 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 m² 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.

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 figure 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.

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.



Fig. 3. Advanced TCS Design Concept

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.

BENEFITS OF GLOBAL BALLOON CONSTELLATIONS

Satellites are expensive because the cost of getting into space is high. High launch costs necessitates higher satellite reliability due to the high investment. Given a typical launch cost of \$50M, the satellite launched will be at least as costly in order to insure that the launch investment is not squandered by premature failures, immature sensors or badly designed spacecraft hardware. While launch vehicles have been getting smaller in order to reduce the per launch costs, the cost per-kilogram-launched has soared for these so-called low-cost launchers. If a network of StratoSats could meet or exceed the requirements of a satellite-based Earth observing system for lower cost, this would be an attractive Earth science option. We have estimated the cost of the example StratoSat design at about \$250k each for a 100-constellation network. Thus a 100 platform constellation would only cost about half as much as a single Delta II launch to low Earth orbit, not counting the satellite on top.

SUMMARY

A revolutionary concept has been described for a global constellation of hundreds of controlled stratospheric superpressure balloons that can cost

effectively address major scientific questions relating to Earth science.



Fig. 4. Example StratoSat Gondola Design

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